USGS
science for a changing world

Report to Congress

Concepts for National Assessment of Water Availability and Use

Circular 1223

U.S. Department of the Interior
U.S. Geological Survey

Report to Congress

Concepts for National Assessment of Water Availability and Use

U.S. Geological Survey Circular 1223

Reston, Virginia
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

Reston, Virginia 2002

Free on application to the
U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

Library of Congress Cataloging-in-Publications Data

Concepts for national assessment of water availability and use / by
Paul M. Barlow... [et al.].
p. cm. -- (U.S. Geological Survey circular ; 1223)
Includes bibliographical references.
ISBN 0-607-98593-3
1. Water-supply--United States. 2. Water use--United States. I.
Title. II. Series.
TD223 .B37 2002
363.6'1'0973--dc21
2002023650

PREFACE

Will there be sufficient freshwater resources in the future to sustain economic growth and the quality of life? In many parts of the country, competition for water to meet the needs of homes, cities, farms, and industries is increasing. At the same time, requirements to leave water in the streams and rivers for environmental and recreational uses are expanding. Water-resources information is needed at many levels to help shed light on overall changing conditions of water scarcity, use, and competition and to help inform discussions about potential changes in water-resource policies and investment plans.

This report responds to a directive from Congress to the U.S. Geological Survey (USGS) to "prepare a report describing the scope and magnitude of the efforts needed to provide periodic assessments of the status and trends in the availability and use of freshwater resources." In response to this directive, the USGS describes in this report efforts needed to develop and report on indicators of the status and trends in storage volumes, flow rates, and uses of water nationwide. This would be analogous to the task of other Federal statistical programs that produce and regularly update indicator variables that describe economic, demographic, and health conditions of the Nation. The assessment also would provide regional estimates of recharge, evapotranspiration, interbasin transfers, and other components of the water cycle. These regional estimates would support analyses of water availability that are undertaken by many agencies and would benefit research quantifying variability and changes in the national and global water cycle.

The effort described would require coordination among many organizations, Federal and non-Federal agencies, and universities to ensure that the information produced can be aggregated with other types of water-availability and socioeconomic information. The efforts identified concerning flows, storages, and uses of water would be used with water-quality information from existing programs to provide a more complete national picture of the quantity and quality aspects of water availability. To maximize the utility of the information, the design and development of these efforts should be coordinated through the Federal Advisory Committee on Water Information.

The assessment would use existing data collected by the USGS and by others to create the indicator variables. Data gaps identified by the program would be coordinated with improvements in data-collection networks for surface water and ground water defined by USGS plans for the National Streamflow Information Program and the Ground-Water Resources Program, and as part of the Cooperative Water Program. Water-use estimation by the program would be strengthened from existing efforts along the lines suggested by the National Research Council.

CONTENTS

BOXES

Concepts for National Assessment of Water Availability and Use

INTRODUCTION

This report responds to the following directive from Congress to the U.S. Geological Survey (USGS) as part of the report on the Fiscal Year 2002 Appropriations for Interior and Related Agencies (House Committee on Appropriations).

> "The Committee is concerned about the future of water availability for the Nation. Water is vital to the needs of growing communities, agriculture, energy production, and critical ecosystems. Unfortunately, a nationwide assessment of water availability for the United States does not exist, or, at best, is several decades old. The Committee directs that by January 31, 2002, the Survey prepare a report describing the scope and magnitude of the efforts needed to provide periodic assessments of the status and trends in the availability and use of freshwater resources."

Water-resources information useful for regional and national assessments of freshwater availability and use requires a continuing process of coordination and collaboration with representatives of the water-users community. During preparation of this report, the USGS solicited input from many individuals and organizations involved in issues of water availability and use (Appendix A). We asked them what types of decisions and policy issues need improved water facts today and in the future, what variables or indicators would be useful, what spatial and temporal scales would be appropriate, how to build on existing efforts, and where to expand collaborative opportunities. In response to our request, we heard from nearly 100 water users, managers, researchers, and advocates through mail and e-mail, phone conversations, and face-to-face meetings.

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.

National Research Council, 2001,
Preface to "Envisioning the Agenda for Water Resources Research in the Twenty-First Century"

There were several clear messages from those with whom we met or corresponded. First, there was consensus that a better set of facts is needed to inform decisions related to water availability. Many individuals emphasized the potential for improved methodologies and standards for consistency of nationwide data, the importance of leaving water in the stream (instream flow) as a component of water use, and the connections between water quantity and water quality. National organizations, in particular, noted the need for consistent indicators of water availability across the Nation. Individuals representing State and local governments reminded us that many States have done extensive planning to quantify water availability now and in the future, and that the availability of water is largely a local issue. Concerns also were expressed that any efforts proposed should not detract from USGS basic data collection nor from USGS partnerships with States and others on local assessments of water availability and use.

There have been several efforts over the past few decades to compile national assessments of water availability. Perhaps the most notable originated from the Water Resources Planning Act of 1965 (Public Law 89–80) that created and empowered the U.S. Water Resources Council to oversee an ongoing study of the Nation's water resources. A rudimentary national assessment was published by the Council in 1968 (U.S. Water Resources Council, 1968), followed by a comprehensive Second National Water Assessment in 1978 (U.S. Water Resources Council, 1978). It has been argued that the primary value of these national assessments was their contribution to the general debate over the definition of national water problems and the direction for national water policy (Osborn and Shabman, 1988).

The U.S. Water Resources Council ceased operations in the early 1980's. In the years that followed, the USGS issued a series of reports under the general title of "National Water Summary" that focused on particular aspects of water resources and provided State-by-State summaries. The first National Water Summary, published in 1984 and referencing 1980 as a base year, documented water-resources issues in each of the 50 States and principal Territories (U.S. Geological Survey, 1984). More recently, as part of the water-sector contributions to the National Assessment of the Potential Consequences of Climate Variability and Change, efforts were made to update components of the Second National Water Assessment to reflect water-availability conditions for the year 1995 (Frederick and Schwarz, 1999).

NATIONAL ASSESSMENT OF WATER AVAILABILITY AND USE

Water availability and use are a function of the total flow of water through a basin, its quality, and the structures, laws, regulations, and economic factors that control its use. Because water availability and water use are closely linked, "water availability" will be used for brevity in the following sections to include both water availability and water use.

It is evident that a national water-availability assessment means different things to different people. Many different types of assessments and assessment products were envisioned by those whose advice was solicited. Recommendations for products included forecasts of water availability, calculations of constructed flow regimes in the absence of human management, calculations of water demands for protection or restoration of wildlife, and an assessment that would include policy-related data linking the institutional and physical environments. The scope and magnitude of an effort to meet all of the recommendations that were received would be an immense undertaking.

A national assessment of water availability is proposed that would report on indicators of the status and trends in storage volumes, flow rates, and uses of water nationwide. Currently, this information is not available in an up-to-date, nationally comprehensive and integrated form. The assessment also would provide regional information on recharge, evapotranspiration, interbasin transfers, and other components of the water cycle across the country. This regional information would support analyses of water availability that are undertaken by many agencies nationwide and would benefit research quantifying variability and changes in the national and global water cycle.

An assessment would require basic hydrologic data collected by the USGS and by others to create the indicator variables. This process of computing indicators from the basic data would help to elucidate uncertainties in our knowledge of the Nation's hydrologic conditions and would provide useful feedback to the design of data-collection networks. Improved networks for the collection of surface-water and ground-water data are defined by USGS plans for the National Streamflow Information Program (U.S. Geological Survey, 1998a and 1999) and the Ground-Water Resources Program (U.S. Geological Survey, 1998b), and as part of the Cooperative Water Program. Water-use information developed by the assessment would expand upon and strengthen existing water-use efforts along the lines suggested by the National Research Council (2002).

There are numerous examples from across the Nation where water quality is the limiting factor to water availability (Box A). Considerable information is currently synthesized about the Nation's water quality at regional and national scales through a number of State and Federal water-quality programs. The USGS National Water-Quality Assessment (NAWQA) program, for example, collects and analyzes water-quality data in many of the Nation's major river basins and aquifers covering nearly all 50 States. Rather than duplicate existing water-quality information, the indicators of the flows, storages, and uses of water developed as part of a national assessment should be used with water-quality information from existing programs to provide a more complete national picture of the quantity and quality aspects of water availability.

A

Quantity *and* Quality of Water Define Availability: An Example from South Florida

Historically, availability of water could be viewed simply as an issue of quantity, and water management could focus largely on controlling or alleviating impacts of droughts and floods. With escalating population growth and increasing demands for multiple water uses, it is now clear that quality is equally critical to the long-term sustainability of the Nation's human communities and ecosystems.

Resolution of water issues at the local and regional scale commonly requires a framework that links both the quantity and quality needs. This framework is perhaps nowhere more evident than for the water-rich South Florida region with its competing uses of water for agriculture, urban growth, and natural-resource protection. An abundant and uncontaminated supply of freshwater was a primary characteristic of southern Florida in predevelopment times. Increased human population and activity, however, have brought not only an increased need for water but also a decrease in water supply and deterioration in water quality (McPherson and Halley, 1996; McPherson and others, 2000).

Before the construction of more than 1,400 miles of primary canals and more than 100 water-control structures, water moved from Lake Okeechobee in a large sheet passing through the Everglades National Park and Big Cypress National Preserve into Florida Bay. Numerous small streams and rivers near the coast drained into mangrove forests and tidal waters and provided the freshwater that sustained the highly productive and abundant coastal fisheries around the southern end of the peninsula.

Approximately 40 percent of that water is now diverted, much of which is used to support heavily irrigated agriculture and urban development along the coast. Such drainage and development have adversely affected water quality and ecology throughout southern Florida. For example, average phosphorus concentrations in Lake Okeechobee have increased two and one-half times over the past 15 years, and massive algal blooms have become more frequent and persistent. In addition, urban uses of water have affected water quality. Stormwater runoff commonly carries heavy metals, nutrients, bacteria, viruses, and pesticides.

Many integrated and collaborative efforts are ongoing to study the Everglades and address some of these conflicting needs for water. For example, recent decisions have been made to set land aside south of the agricultural area to help remove nutrients before the water moves farther southward. Additionally, water is being recycled from agricultural lands back to the fields, instead of moving south toward Florida Bay, thus holding back nutrients and reducing water demand. Water conservation in the urban areas may well stabilize, or even decrease, the population demands for water. Water issues in South Florida demonstrate that water availability challenges every region of the Nation where sufficient quantity and quality of water are needed to sustain the many competing demands for the resource.

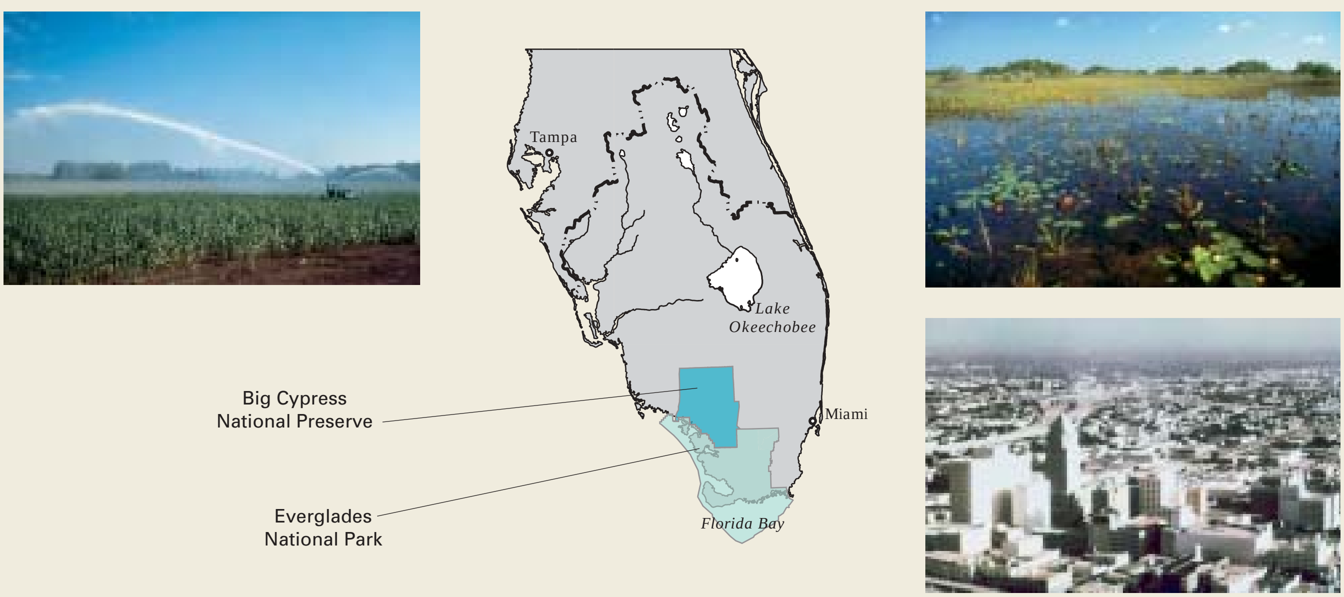
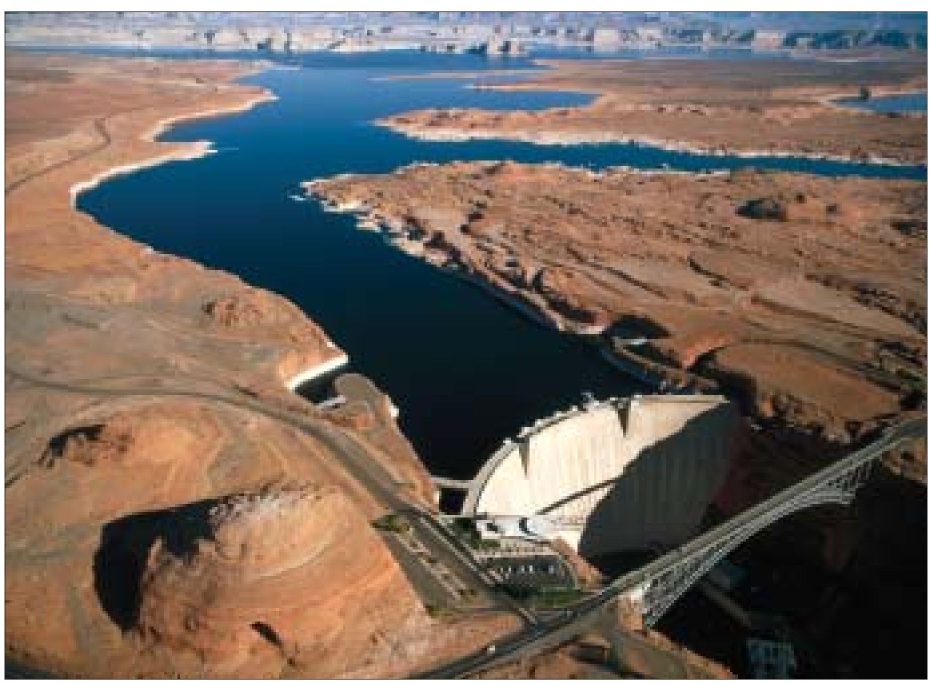


Figure A–1. *Competition for water to meet the needs of cities, farms, industries, and critical ecosystems challenges every region of the Nation, including south Florida where urbanization and agricultural activities have altered the hydrologic environment. Left, irrigation of crops in southern Everglades C–111 agricultural basin; upper right, northern Everglades; lower right, aerial view of Miami. Photographs by Benjamin F. McPherson.*

Coordination and Collaboration

The goals of a national assessment are consistent with the mission of the USGS to provide scientific information to support decision-making on issues of resources, environmental quality, and natural hazards. An effort to develop the national indicators of water availability and the water-cycle information should be done in coordination and collaboration with other organizations, Federal and non-Federal agencies, and universities. Collaboration across agency boundaries would ensure that information produced could be aggregated with other types of physical, social, economic, and environmental data that affect water availability. Data that are germane to issues of water availability include water-quality conditions, population statistics, land uses, water costs and pricing, climate data, and instream-flow requirements for aquatic habitats. These data are compiled by State and local agencies, by universities and water-resource organizations, and by several Federal agencies including the Department of Agriculture, the National Oceanic and Atmospheric Administration, the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the U.S. Environmental Protection Agency. Such an assessment could include external research grants and contracts that would be used to improve the methodology and understanding of water availability and to gather, analyze, and disseminate program results.

The assessment should coordinate the design and development of water-availability indicators and water-cycle information through the Federal Advisory Committee on Water Information (ACWI). ACWI members represent 35 organizations from all levels of government (Federal, State, Tribal, and local), public interest groups, academia, private industry, and nonprofit and professional organizations. ACWI is chaired by the Deputy Assistant Secretary of the Interior for Water and Science and is staffed and supported by the USGS under a charter established pursuant to the Federal Advisory Committee Act by Office of Management and Budget Memorandum 92–01. ACWI currently has several subgroups examining water-quality monitoring, data methods and comparability, spatial water data, hydrology, stream gaging, cooperative water programs, and science issues. An additional subgroup should be established to make recommendations on the design and methods of presentation of the proposed indicators of flows, storages, and uses of water and the integration of these indicators with water-quality information and other measures of water availability.



Glen Canyon Dam impounds the Colorado River and Lake Powell near the Arizona-Utah border. The reservoir storage content of Lake Powell is monitored by the Bureau of Reclamation. Photograph by Michael Collier.

Indicators of Water Availability

An assessment should develop and report up-to-date, nationally consistent indicators that would reflect the status and trends in water availability nationwide. Indicators would be developed for surface-water flows and storage, ground-water levels and storage, and water use (table 1). Data sets and analyses produced by the proposed assessment would be posted on the Internet and published in reports and scientific journals. Efforts to develop indicators should comply with the Office of Management and Budget Information Quality Guidelines.

There are several spatial scales at which the indicators of water availability could be reported. Past assessments have focused on the individual States and the 21 major water-resources regions of the United States (fig. 1). Because of technological advances for managing, presenting, and sharing spatial data, it is now possible to provide information at a more refined scale needed by decision-makers.

An assessment should use the 352 river-basin hydrologic accounting units (fig. 2) as the basis for reporting the national indicators. These accounting units are watersheds that are typically from 5,000 to 20,000 square miles and are used by the USGS for designing and managing the National Water Data Network (Seaber and others, 1987). In most cases, however, boundaries of the hydrologic accounting units do not coincide with those of major aquifer systems. Ground-water variables, therefore, should be reported primarily by major aquifer system.

Table 1. *Summary of proposed indicators of water availability*

Surface-water indicators
Streamflow: annual and periodic (5- to 10-year) summaries; assessments of long-term trends
Reservoir storage, construction, sedimentation, and removal
Storage in large lakes, perennial snowfields, and glaciers
Ground-water indicators
Ground-water-level indices for a range of hydrogeologic environments and land-use settings
Changes in ground-water storage due to withdrawals, saltwater intrusion, mine dewatering, and land drainage
Number and capacity of supply wells and artificial recharge facilities
Water-use indicators
Total withdrawals by source (surface water and ground water) and sector (public supply, domestic, commercial, irrigation, livestock, industrial, mining, thermoelectric power, and hydropower)
Reclaimed wastewater
Conveyance losses
Consumptive uses

In testimony before the Environment and Public Works Committee, Subcommittee on Fisheries, Wildlife and Water, on November 14, 2001, Ane D. Deister, Co-Chair of the Interim National Drought Council, identified the following areas as needing coordinated data collection, analysis, and evaluation:

- *Ground-water supplies and recharge and extraction rates of aquifers*
- *Water-use consumption, demand forecasting, and accurate estimates of water supply and demand balance*
- *Conservation measures in urban, agricultural, commercial, institutional and industrial sectors*
- *Stream gages and other watershed monitoring*
- *Weather prediction and long-term patterns and trends*

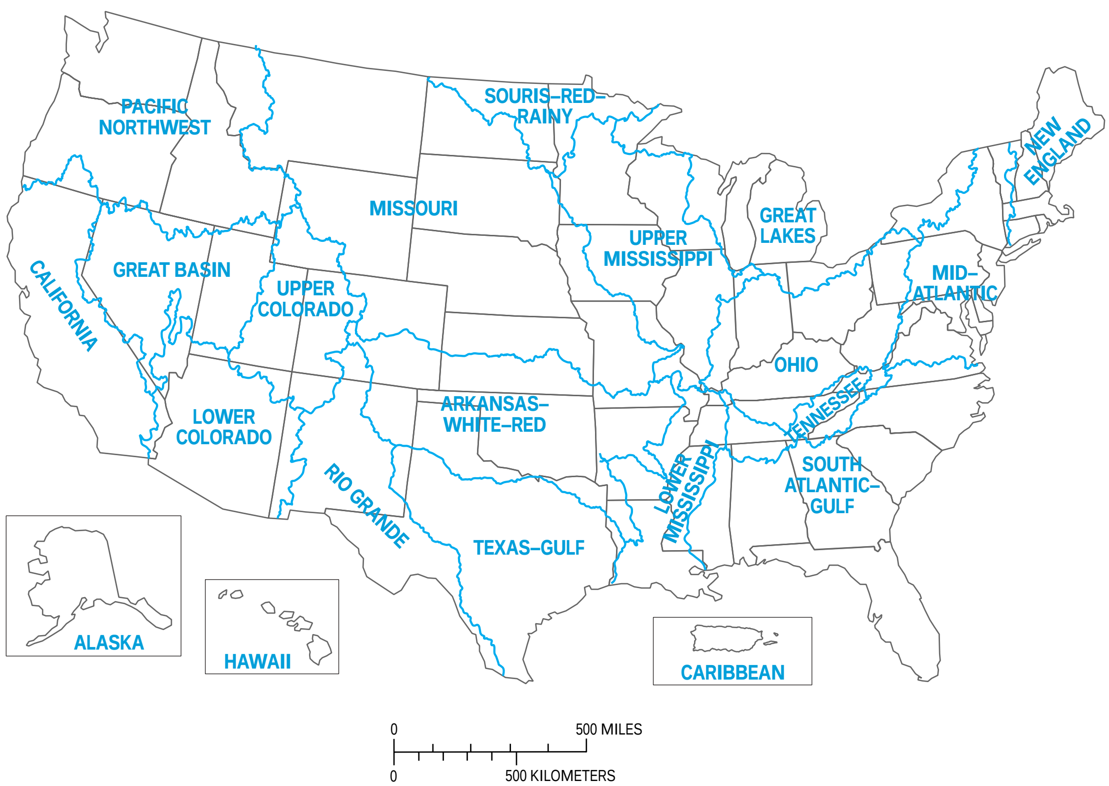


Figure 1. *Water-resources regions of the United States (U.S. Geological Survey, 1982).*

Water availability varies seasonally and from year to year in response to changing weather conditions and water-use demands. A meaningful national assessment must remove seasonal and short-term variability to isolate trends and patterns that have regional and national significance. Hence, the status and trends of most indicators should be reported and evaluated every 5 to 10 years. To place these periodic evaluations into long-term perspective, an initial retrospective assessment of the past 100 years should be undertaken to reveal, to the extent possible, changes in water availability during the 20th century. In addition, annual reporting of some indicators, such as surface-water flow, should be done to provide an indication of year-to-year variability of water availability. Monitoring networks for surface-water flow are sufficiently developed to allow for annual reporting and evaluation.

Knowledge about hydrologic fluctuations with durations of decades to centuries is important because the lifetimes of man-made water resource systems and of the consequences of resource management decisions are often of comparable duration.

Water Cycle Study Group, U.S. Global Change Research Program, May 2001 (Hornberger and others, 2001, p. 11)

SURFACE WATER

Indicators of surface-water availability would include measures of both streamflow and surface-water storage, each of which change continuously in response to natural and human-induced processes (table 2).

Streamflow

Currently, the USGS provides a number of assessment-type streamflow products at daily, weekly, and monthly time scales. These products, such as the online *Water Watch* Internet site of maps and graphs (fig. 3), are useful to emergency managers, public officials, and others tracking floods and droughts and to private citizens planning recreational activities. The USGS will continue to produce these types of information on daily to monthly conditions through our existing programs.

Streamflow indicators that support longer term water-availability decisions require more interpretive, value-added information at annual and longer time scales than is currently obtainable. To fulfill these longer term requirements, the following three specific types of streamflow indicators would need to be produced:

- Annual summaries (graphical and tabular) of surface-water discharge for each of the 352 hydrologic accounting units of the United States: Annual summaries would provide simple and concise representations of the net effects of climatic events, water management, and water withdrawals on surface-water supply during a year, as well as from one year to the next.
- Periodic summaries of changes in surface-water discharge for each hydrologic accounting unit over periods of 5 to 10 years: Historically, some regions of the United States are predisposed to persistent periods of wetness or dryness. These periods can last a decade or more. To evaluate such persistent patterns and to gage their overall severity, periodic summaries of interannual change in surface-water supply are needed.
- Periodic assessments of long-term trends in surface-water discharge in each hydrologic accounting unit: The ability to determine systematic long-term changes in surface-water supplies is an important capability of the national stream-gaging network. Recent questions associated with global climate and related environmental change increase the imperative for periodic assessments of trends in the Nation's water supply at regional and national scales.

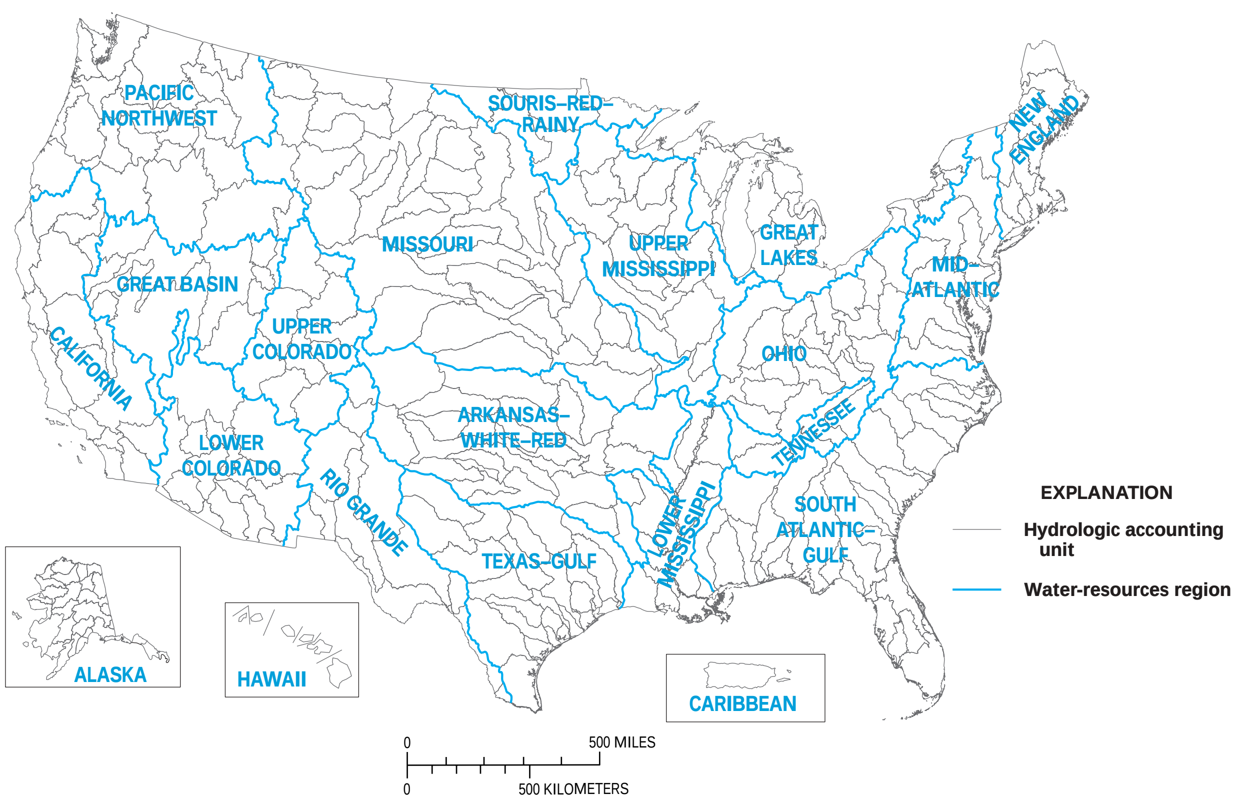


Figure 2. *Hydrologic accounting units of the United States (U.S. Geological Survey, 1982).*

An example of the kind of information that can be discerned by analysis of long-term (multi-decadal) streamflow records across the Nation is given in figure 4, which depicts changes in the annual 7-day low flow for selected unregulated (fig. 4*A*) and regulated (fig. 4*B*) rivers. The annual 7-day low flow can be used as an indicator of hydrologic drought. The graphs in figure 4*A* indicate long-term low-flow changes on rivers that are minimally affected by surface-water diversions and reservoirs and are, therefore, more reflective of climatic variations. They provide a means of determining how annual dryness (including drought) has changed through time; for example, have droughts become more or less frequent or severe? In contrast, the graphs in figure 4*B* indicate changes on rivers where human activities have altered the natural flow, such as by dams and diversions. As such, they not only reflect the influence of climate but also provide information on how and where human activities have affected low streamflow and drought. In combination, the two sets of graphs give resource managers and policy makers important information on how and where low-flow conditions are changing around the Nation.

As part of the streamflow indicators, the assessment would provide an accounting of the status and trends in the availability of water for instream uses in various parts of the country by defining the amount of water remaining in a stream after offstream uses. Because instream-flow requirements can be estimated only by detailed analysis of local situations, an assessment would not estimate them.

Table 2. *Mechanisms that cause changes in streamflow and surface-water storage*

Natural mechanisms	Human-induced mechanisms
Runoff from rainfall and snowmelt	Surface-water withdrawals and transbasin diversions
Evaporation from soil and surface-water bodies	River-flow regulation for hydropower and navigation
Transpiration by vegetation	Construction, removal, and sedimentation of reservoirs and stormwater detention ponds
Ground-water discharge from aquifers	Stream channelization and levee construction
Ground-water recharge from surface-water bodies	Drainage or restoration of wetlands
Sedimentation of lakes and wetlands	Land-use changes such as urbanization that alter rates of erosion, infiltration, overland flow, or evapotranspiration
Formation or dissipation of glaciers, snowfields, and permafrost	Wastewater outfalls
	Irrigation wastewater return flow

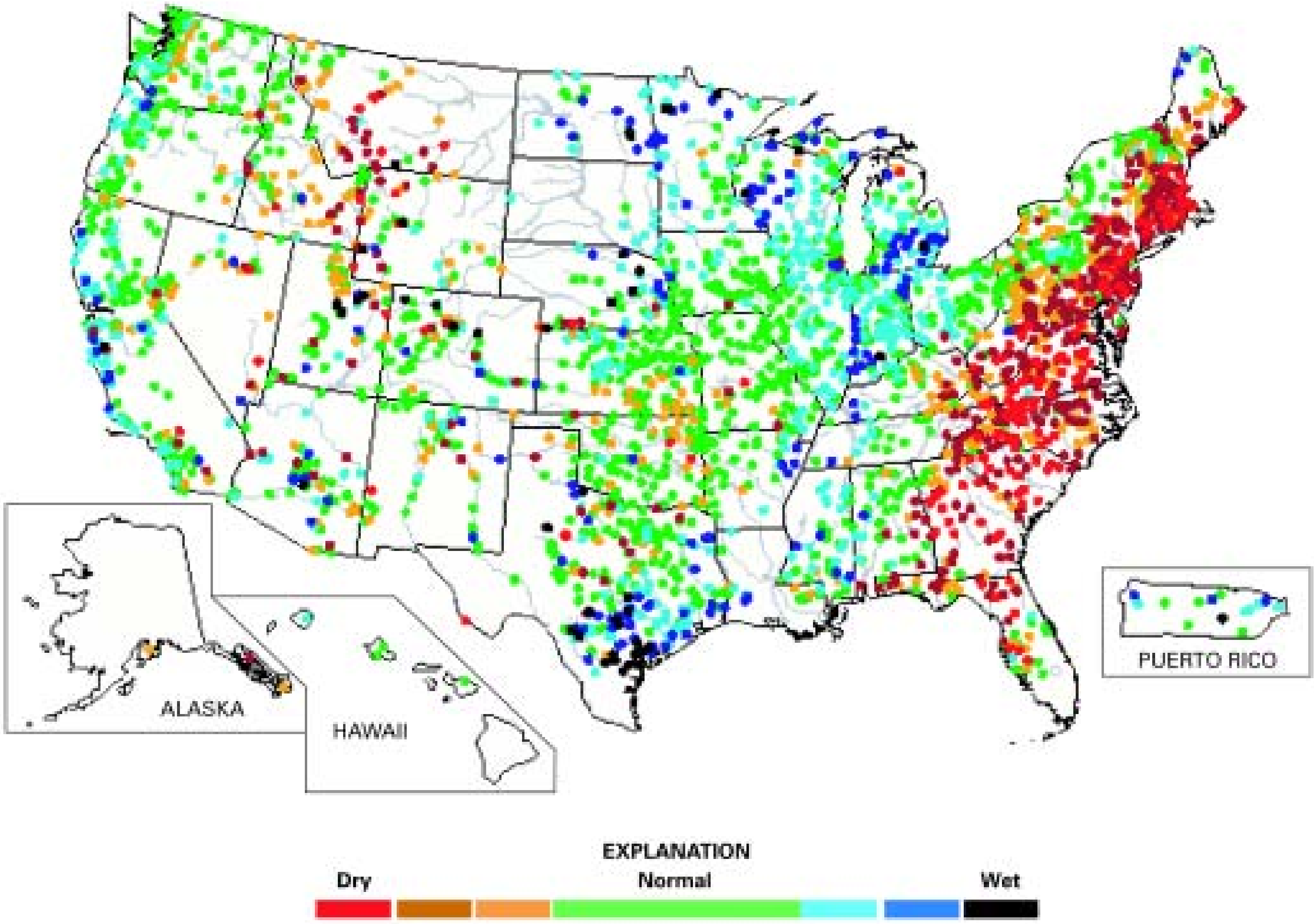


Figure 3. *Near-realtime streamflow map of the United States, December 5, 2001 (U.S. Geological Survey, 2001). Streamflow conditions across the country are reported daily by maps and graphs on the U.S. Geological Survey* Water Watch *Internet site (http://water.usgs.gov/waterwatch/).*

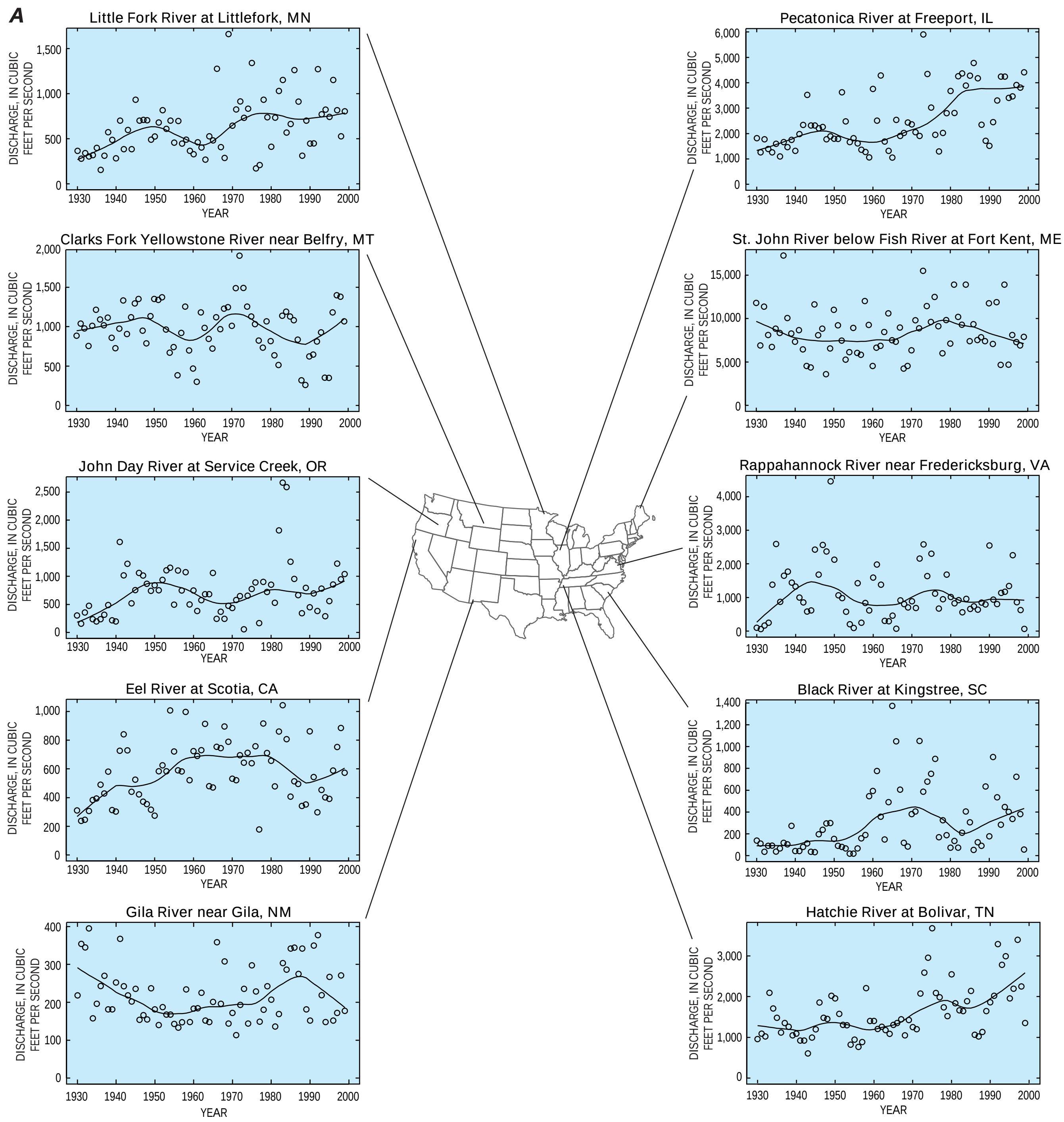


Figure 4. *The ability to determine systematic long-term changes in surface-water availability is an important capability of the national stream-gaging network maintained by the USGS. These graphs show annual 7-day low flow for the 70-year period from 1930 to 1999 on selected unregulated (A) and regulated (B) rivers. The annual 7-day low flow is a streamflow statistic that is often used as an indicator of hydrologic drought. Years when the annual 7-day low flow is relatively low typically correspond with drought or abnormally dry periods. The plots in figure 4A depict long-term changes in low flow on rivers that are not significantly affected by surface-water diversions and reservoirs, whereas those in figure 4B depict long-term changes in low flow on rivers where human activities have altered the natural flow, such as by dams and diversions. By assessing both situations, it is possible to determine how, where, and why hydrologic drought is changing in the United States.*

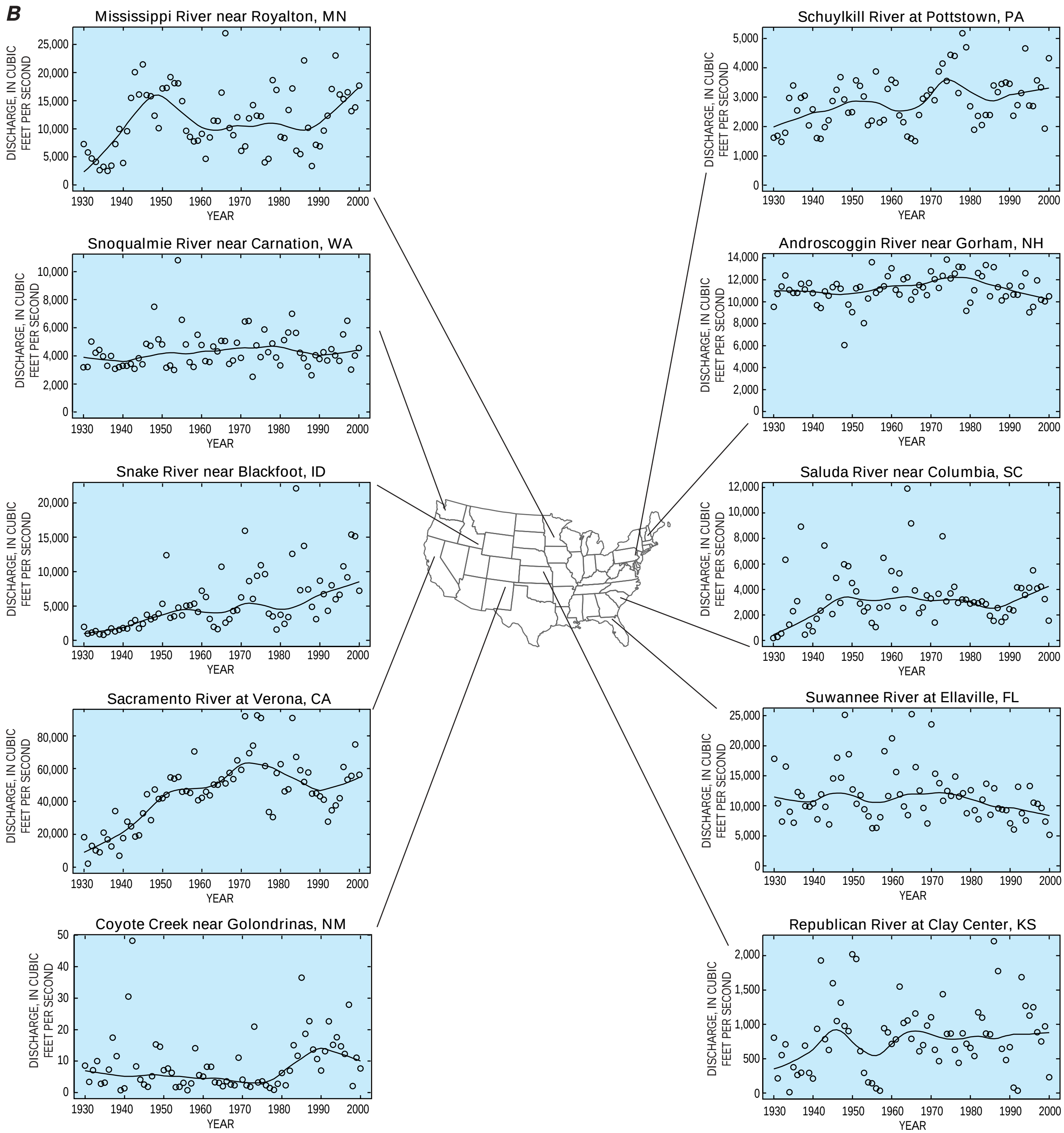


Figure 4.—*Continued.*

Surface-Water Storage

Indicators of the status and trends in surface-water storage would consist of annual summaries of storage conditions within each of the hydrologic accounting units; periodic summaries of changes in surface-water storage for each hydrologic accounting unit over periods of 5 to 10 years; and periodic assessments of long-term trends in surface-water storage in each hydrologic accounting unit. The indicators would account for storage changes in surface reservoirs and in selected natural fresh-water bodies, including large lakes such as the Great Lakes and Lake Champlain, perennial snowfields, and glaciers.

The primary changes in surface-water storage in most basins arise from changes in the total capacity of, and conditions within, surface reservoirs. Reservoir construction in the United States and Puerto Rico peaked during the 1960's and has slowed markedly since then (fig. 5). Presently, there are nearly 77,000 dams higher than 6 feet in the United States and Puerto Rico (U.S. Army Corps of Engineers, 2001). Because some reservoirs have multiple dams, this corresponds to about 68,000 reservoirs nationwide. Omitting dams that are control structures on large natural lakes, such as Superior or Okeechobee, the total volume of water stored in these reservoirs under typical conditions is about 422 million acre-feet (520 cubic kilometers) (Stallard, 1998).

Total reservoir storage conditions change in response to hydrologic and water-use variability, reservoir sedimentation, and reservoir construction and removal. An assessment would regularly update reservoir storage conditions and account for construction of new reservoirs, decreases in reservoir storage capacity due to sedimentation, and any removal of dams. The RESIS (Steffen, 1996) and RESIS-II (Stallard and others, 2001) databases of sediment deposition in U.S. reservoirs would serve as the basis for evaluating changes in reservoir sedimentation. These databases track losses in reservoir storage capacity throughout the United States and are the master databases for regional erosion studies (Stallard, 1998).

Development of indicators of surface-water storage would require close coordination with many agencies and groups because most reservoir data are collected and maintained primarily by agencies other than the USGS. A primary source of information on dams and reservoirs is the National Inventory of Dams, which is maintained by the U.S. Army Corps of Engineers in cooperation with the 50 States, Puerto Rico, the Association of State Dam Safety Officials, and 16 other Federal agencies. Additional data are available from city and State agencies and water districts that oversee or operate dams and reservoirs. Moreover, a large number of Federal and other governmental agencies presently monitor surface-water levels and reservoir storage on a continuing basis.

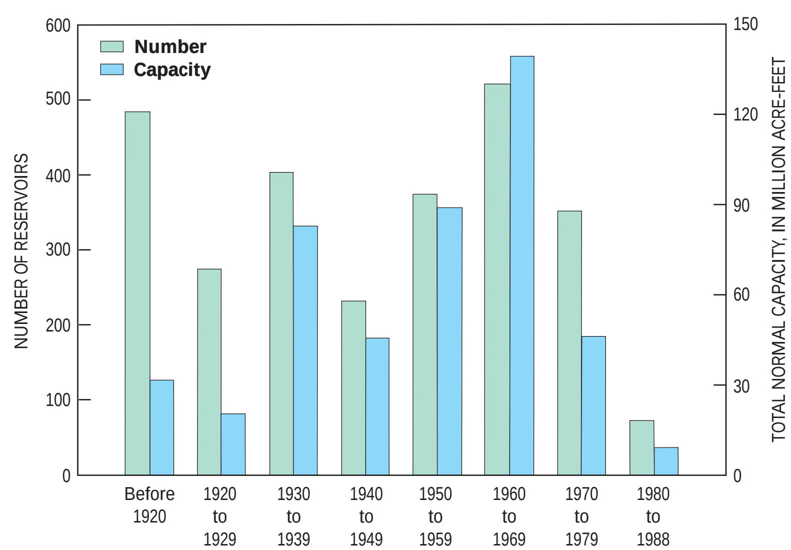


Figure 5. *Reservoirs are important indicators of water availability. The graph shows the number and total normal capacity of large reservoirs in the United States and Puerto Rico completed before 1920, during each decade from 1920 to 1979, and from 1980 to 1988. Normal capacity is the total volume in a reservoir below the normal retention level (figure from Ruddy and Hitt, 1990).*

GROUND WATER

Long-term, systematic measurements of ground-water levels provide essential data needed to evaluate changes in ground-water storage over time. Using these data, the assessment would include two types of indicators to describe the nationwide status and trends of ground-water availability: ground-water-level indices and periodic assessments of changes in ground-water storage.

No nationwide, systematic ground-water-level monitoring program exists. At present there are approximately 42,000 long-term observation wells in the United States that have 5 or more years of water-level records (Taylor and Alley, 2002). The density of existing monitoring wells, however, varies considerably from State to State (fig. 6). The extent of water-level monitoring varies even more among major aquifers, with very limited monitoring in many aquifers. Thus, an inventory of existing water-level networks for major aquifer systems would be made early in the assessment to identify data gaps and opportunities for collaboration across the Nation.

Ground-Water Levels

The assessment should develop several indices of ground-water-level changes; some would represent composite indices for the Nation, whereas others would be analogous to "sector" indices in the stock market and would reflect specific geographic regions or specific types of aquifers, terrains, environments, or land-use settings. The various indices would provide water managers, major water users, and the public with quick summaries of the magnitudes and significance of trends in water-level changes.

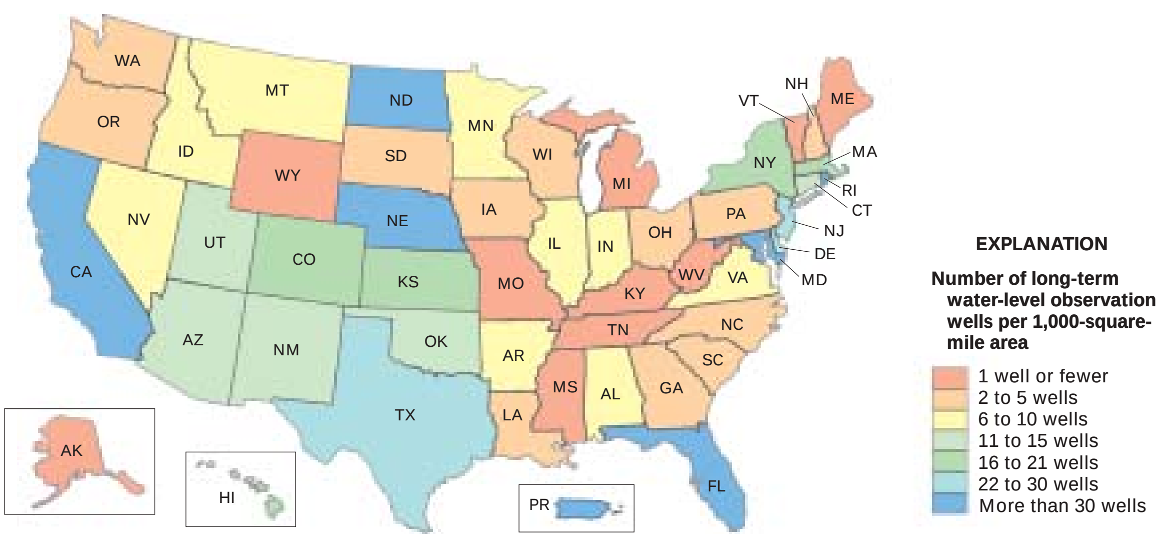


Figure 6. *Number of ground-water-level observation wells having at least 5 years of water-level record per 1,000-square-mile area in each State and in Puerto Rico (modified from Taylor and Alley, 2002).*

Table 3. *Mechanisms that cause changes in ground-water levels and storage (modified from Freeze and Cherry, 1979)*

Natural mechanisms	Human-induced mechanisms
Recharge	Ground-water withdrawals
Evaporation from the water table	Deep-well injection
Transpiration by vegetation	Agricultural irrigation
Discharge to streams, springs, and seeps	Drainage of agricultural lands, swamps, and wetlands
Surface-water-level fluctuations in hydraulically connected streams, ponds, or lakes	Artificial recharge of water
	Wastewater recharge through lagoons, landfills, and septic systems
	Dewatering of mines, tunnels, or other structures
	Leakage from surface-water reservoirs
	Urbanization impacts such as leaky water and sewer lines, lawn irrigation, and impervious surfaces (paved roads, parking lots, and so forth)

To have national or even regional significance, indices of ground-water levels have to be based on repeated observations at relatively large numbers of observation wells located in a wide range of representative hydrogeological environments. Ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawals, and land uses. Water levels in wells change in response to a number of types of local and regional stresses, some of which are natural and some of which are human induced (table 3). Because subsurface hydraulic properties are highly variable, water-level responses to stresses vary considerably with location and depth. Stresses take time to propagate through ground-water systems, so water-level changes are transient phenomena that are strongly affected by distances from the monitoring wells to imposed stresses.

Ground-water-level monitoring networks should include wells open to water-table aquifers and deep artesian aquifers, wells tapping a variety of rock types, wells located both near and distant from pumping centers, wells located in typical land-use settings, and wells that are widely distributed geographically. Because the magnitude of water-level fluctuations in wells depends on many factors, water levels in some wells may fluctuate by tens of feet within a day, but in other wells, water levels may change by only tenths of a foot over a year. Therefore, some wells may need to be monitored continuously, whereas others may only need to be measured once per year. Among the several indices that would be derived for this assessment, some might be updated daily, others might be updated monthly, and still others annually.

Ground-Water Storage

The amount of ground water in storage in the United States is changing (mostly decreasing) in response to ground-water withdrawals and other mechanisms shown in table 3. Data from several ground-water basins and aquifers already show significant depletions in freshwater availability over several decades. An example showing the greatest depletion (or ground-water mining) is the High Plains aquifer of the central United States, where ground-water withdrawals—primarily for irrigation—have caused large-scale, regional declines of the water table and accompanying reductions in ground-water storage (Box B).

Periodic national assessments of changes in aquifer storage due to ground-water withdrawals, saltwater intrusion, mine dewatering, land drainage, and other mechanisms that affect ground-water availability should be undertaken. These assessments would be based on nationwide summaries of observed water-level changes and ancillary data describing the aquifers and their changing storage conditions. These assessments would require a greater level of effort than that required for development of the ground-water-level indices because estimates of changes in ground-water storage require knowledge of aquifer storage properties and spatial interpolation of ground-water-level measurements. The assessment also could provide measures of the nationwide status of ground-water-supply infrastructure, such as changes in the number and capacity of water-supply wells and artificial recharge facilities; these measures would be analogous to those reported for surface-water reservoirs.

Changes in ground-water use and the effects of ground-water development are not usually as variable year to year as are those for surface water and, therefore, the periodic assessments of ground-water storage could be made at 5- to 10-year intervals. Ground-water-storage changes should be evaluated by major aquifer and then aggregated into regional and national assessments. A retrospective analysis of changes in ground-water storage during the 20th century would be made at the beginning of the assessment. In some cases, historical changes in ground-water storage may need to be estimated by use of ground-water simulation models that account for all ground-water storage processes, including storage changes in confining units. This modeling would build, in part, on work from the USGS Regional Aquifer-System Analysis (RASA) Program, which studied and modeled the Nation's regional aquifers from 1978 to 1995.

Changes in ground-water storage over the past 100 years may be large enough to have global implications. If the volume of ground water stored on the continents has decreased significantly over the past century, then it might represent and account for a measurable fraction of the sea-level rise observed during that time period. This would have implications for global climate modeling and predictions of future sea-level rise. The impact of ground-water declines could be offset by increases in water stored in reservoirs, so global impacts must be assessed in light of both components of water storage. An assessment of changes in ground-water storage in the United States perhaps could be integrated into a global perspective in collaboration with other countries and international organizations.

By pumping the vast reserves of ground water, farmers have developed the San Joaquin Valley of California into a major agricultural region. Photograph courtesy of the California Department of Water Resources.

Water-Level Monitoring and Ground-Water Depletion in the High Plains Aquifer

Ongoing water-level monitoring in the High Plains aquifer documents the long-term ground-water depletion of a national resource and provides a good example of the type of water-level network required to assess ground-water availability in the Nation's major aquifer systems. The High Plains aquifer is a 174,000-square-mile area underlying parts of eight States from South Dakota to Texas. Irrigation water pumped from the aquifer has made the High Plains one of the Nation's most important agricultural areas.

The intense use of ground water has caused major water-level declines and reduced the saturated thickness of the aquifer (the ground water remaining in storage) in some areas to a level at which it is no longer economical to use the aquifer as a water supply. The changes are particularly evident in the central and southern High Plains (fig. B–1), where more than 50 percent of the predevelopment saturated thickness has been dewatered in some areas.

Water-level declines increase pumping lift, decrease well yields, and limit development of the ground-water resource. The net amount of water removed from storage in the aquifer is estimated to have been 220 million acre-feet (270 cubic kilometers) through 1999. This is a very large volume of freshwater—equal to more than half the volume of water in Lake Erie. If the total volume depleted from this single, multi-State aquifer was spread over the surface of the oceans, it would raise sea level about 0.75 millimeter, or about 0.5 percent of the sea-level rise observed during the entire 20th century.

In response to declines in water levels and ground-water storage (fig. B–2), a monitoring program was begun across the High Plains in 1988 to assess annual ground-water-level changes in the aquifer. Water-level measurements have been made each year in more than 7,000 wells. This substantial effort requires collaboration among numerous Federal, State, and local water-resource agencies. Water levels continue to decline in many areas of the aquifer, but the monitoring program indicates overall reductions in the rate of decline during the past two decades in some areas (McGuire and Sharpe, 1997). This change is attributed to decreases in irrigated acreage, reduced water needs because of improved irrigation and cultivation practices, and above-normal precipitation and recharge during this period.

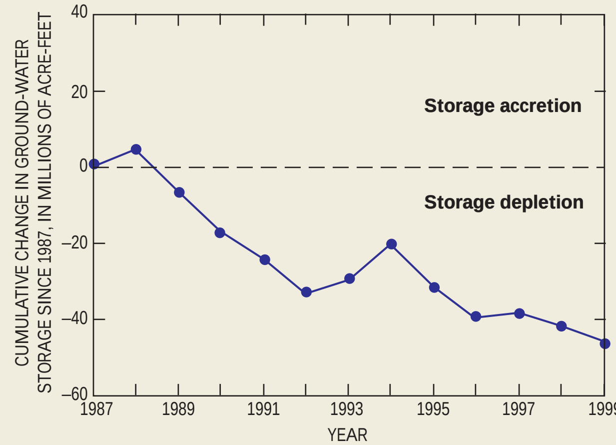


Figure B–2. *Cumulative changes in ground-water storage in the High Plains aquifer system since 1987.*

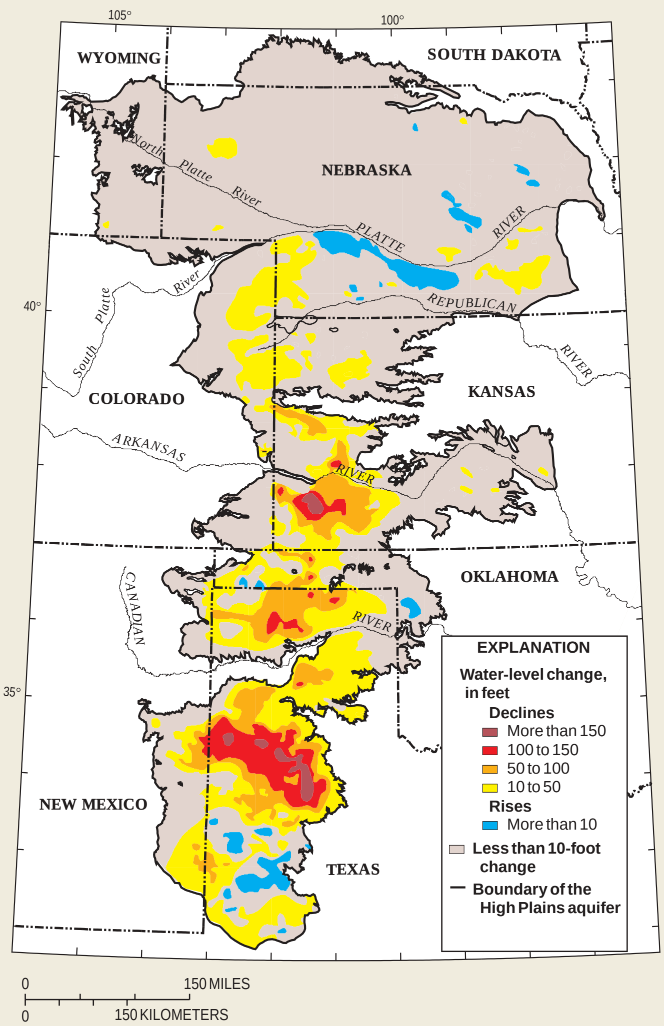


Figure B–1. *Changes in ground-water levels in the High Plains aquifer from before ground-water development to 1997 (V.L. McGuire, U.S. Geological Survey, written commun., 1998).*

WATER USE

Existing water-use estimation efforts need improved coordination and analysis of program effectiveness to reflect the increased importance of, and demands for, national water-use data and analyses. The USGS has compiled and disseminated estimates of water use for the Nation at 5-year intervals since 1950 (Solley and others, 1998). Water-use information is compiled in collaboration with the States through the USGS Cooperative Water Program. Differences among the States in the types of water uses, in funding priorities, and in regulations that require reporting of water-use information have resulted in an unevenness in the breadth and depth of water-use data collected for each State.

A goal of this element of an assessment is to strengthen and enhance future studies of the Nation's water use along the lines recommended by the National Research Council (NRC) in a recent review of the USGS water-use program (Box C). A key recommendation of the NRC review was to use sampling strategies and mathematical (regression) modeling to develop statistically derived water-use estimates. This statistical approach, which could be undertaken as part of the assessment, would identify demographic, economic, geologic, hydrologic, and climatic indicators that are correlated with water use and that can be used to supplement existing water-use data. Statistical correlations developed between water use and these related indicators might allow improved understanding of past trends in water use and better prediction of future changes in water demands and water uses. Estimates of irrigation water use, for example, are well suited to statistical applications because irrigation withdrawals are closely related to indicators such as climate, farming and irrigation techniques, and irrigated acreage (fig. 7). Reshaping the national water-use data-collection strategies by using statistical techniques also would help to develop consistent methods for estimating water use across State and regional boundaries.

Under such an assessment, water-use estimates would be provided at 5-year intervals by county, State, and major water-resources regions of the Nation. As statistical techniques are developed, the assessment would move toward annual accounting of high-priority water-use sectors such as public supply and irrigation. In addition, efforts would be made to develop water-use estimates for each of the 352 hydrologic accounting units and for the Nation's major aquifer systems. As in previous water-use assessments, State agencies would be a major partner in the collection and reporting of water-use indicators.

An enhanced national water-use database would be developed and maintained to provide ready access to water-withdrawal, conveyance, and return-flow information. The database also would store ancillary data sets on the related water-use indicators. Some of the data sets for these related indicators are available from State agencies and other Federal agencies, such as the Department of Agriculture, Department of Energy, Bureau of Economic Analysis, and Bureau of the Census. Consistent and accessible water-use data made available through a national water-use database would be the foundation for integrating water-use data with water-flow and water-quality data to generate policy-relevant information about human impacts on water and ecological resources.

Center pivot irrigation system, Kansas. Photograph by Kevin F. Dennehy.

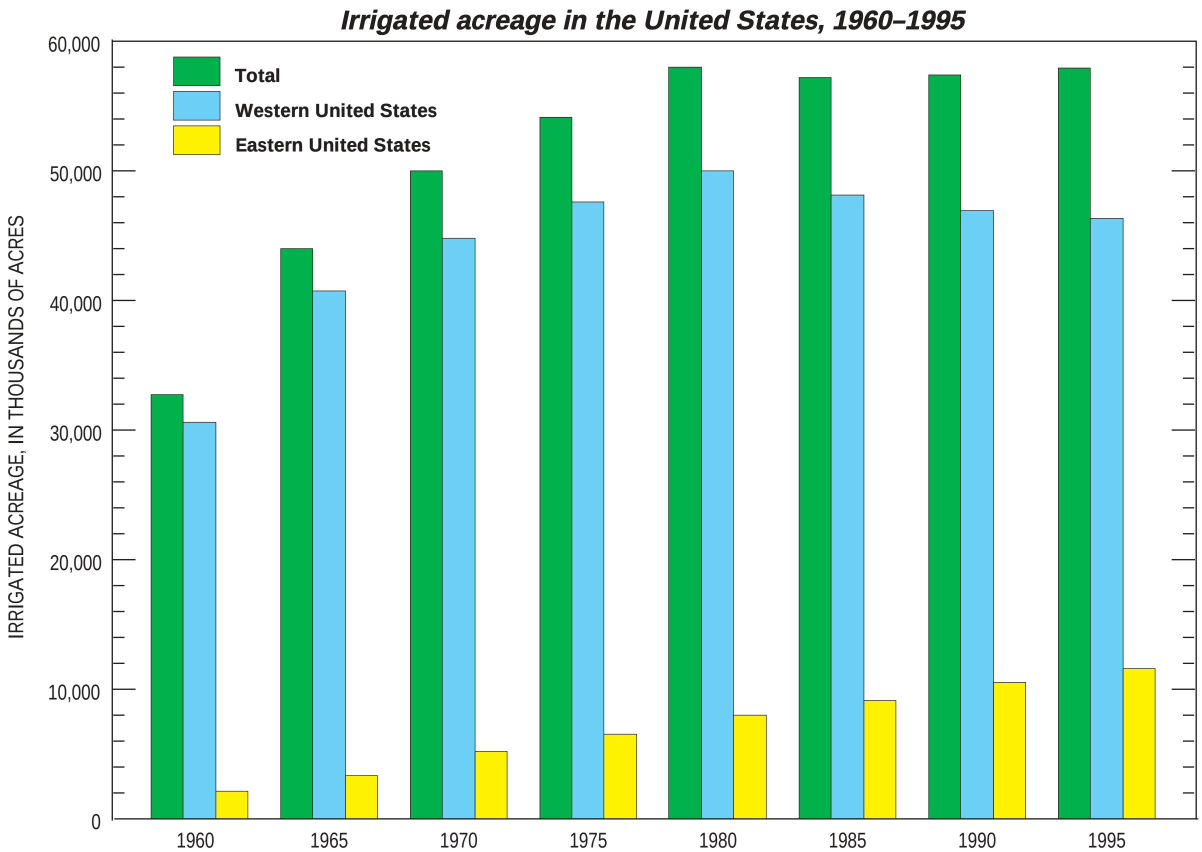


Figure 7. *Nationally, withdrawals for irrigation are a large percentage of total water use, accounting for 40 percent of total withdrawals and 80 percent of consumptive uses in 1995 (Solley, 1998). Total irrigation withdrawals and irrigated acreage in the United States steadily increased between 1960 and 1980, but then declined in 1985 and has remained fairly steady since. The decrease in irrigated acreage in the West is a result of expanding urban areas and an increase in dryland farming. In contrast, irrigated acreage in the East increased steadily over the same 35-year period, especially in areas with favorable climate, topography, and available water. (Data compiled from U.S. Geological Survey Circulars titled "Estimated use of water in the United States" published in 5-year intervals between 1960 and 1995.)*

C

A Plan to Enhance the National Water-Use Information Program

The National Research Council Committee on USGS Water Resources Research recently conducted a review of the National Water-Use Information Program (NWUIP) to determine the best approach for future studies of water use by the USGS (National Research Council, 2002). The following are some of the findings and recommendations of the Committee to the USGS:

- The NWUIP is the Nation's only comprehensive source of information on the status and trends of water use. The USGS is uniquely suited to provide this essential national information, working with its State-level cooperative partners and with other Federal agencies.

- The NWUIP should be viewed as much more than a data-collection and database management program. The NWUIP should be elevated to a *water-use science* program, emphasizing applied research and techniques development in both the statistical estimation of water use, as well as the determinants and impacts of water using behaviors.

- To better support water-use science, the USGS should build on existing data-collection efforts to systematically integrate data sets, including those maintained by other Federal and State agencies, within the data-collection and water-use estimation activities of the NWUIP.

- The USGS should systematically compare water-use estimation methods to identify the techniques best suited to the requirements and limitations of the NWUIP. One goal of this comparison should be to determine the standard error for every water-use estimate.

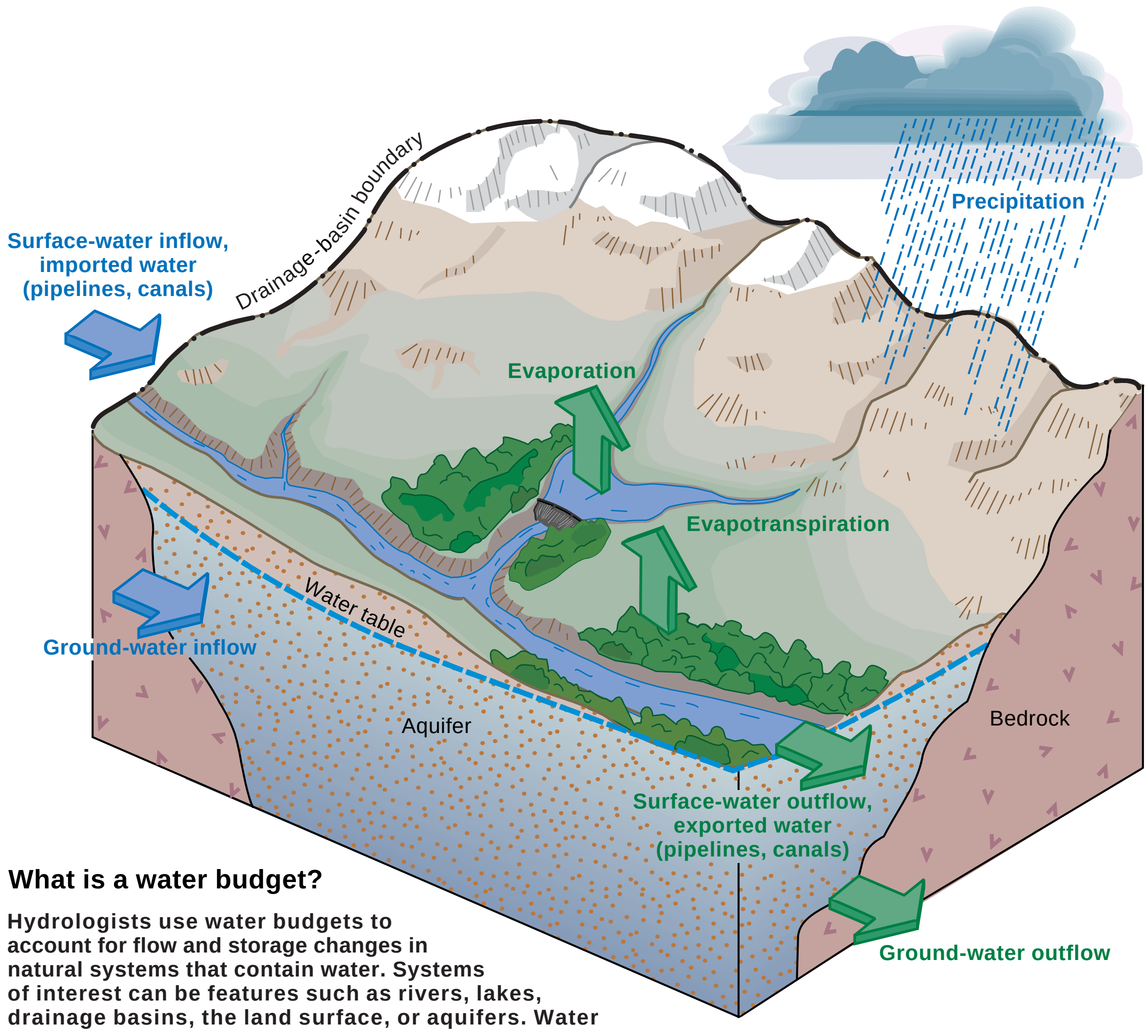
- The USGS should focus on the scientific integration of water use, water flow, and water quality, to expand knowledge and generate policy-relevant information about human impacts on both water and ecological resources.

Water-Cycle Characterization

Many of those who provided input regarding a national assessment of water availability indicated a need for improved regional-scale estimates of recharge, evapotranspiration, interbasin transfers, and other components of the water cycle. Elements of the water cycle typically are organized and interpreted in terms of water budgets (fig. 8). State, local, and Federal water managers often rely on the USGS for quantitative information on water-cycle components to better understand water budgets and to support water-management decisions. Information on water-cycle components for regional water budgets, however, is not always available in a consistent form across the Nation. To meet these information needs, the assessment should provide regional estimates of selected water-cycle components across the Nation. These estimates would support analyses of water availability that are undertaken by many local and regional agencies, would benefit research quantifying variability and changes in the national and global water cycle, and would aid in the interpretation of trends identified in the national indicators of water storage, flow, and use. Some of the water-cycle components, such as evapotranspiration, have proven difficult to estimate accurately using existing measurement techniques. Therefore, the assessment should support development of improved methods for quantifying water-cycle components.

The effort for improved characterization of water-cycle components outlined here would complement, build upon, and extend the gains made through the existing USGS Cooperative Water Program. The Cooperative Water Program is a cost-sharing partnership between the USGS and water-resource agencies at the State, local, and Tribal levels. As part of the cooperative program, the USGS conducts analyses of water availability in support of water-resource management decisions from local to statewide levels. These analyses often are done to estimate specific components of the water cycle or to quantify interactions among multiple components of the water cycle.

Two examples from the USGS Cooperative Water Program illustrate the value of water-cycle information for water-resource management, as well as the level of effort that is required for water-cycle studies. In the Eastern United States, the USGS is studying interactions among water withdrawals, streamflow reductions, and streamflow requirements for aquatic-habitat protection (Box D). In the Southwest, the USGS developed improved methods for estimating evapotranspiration by native vegetation to better understand the water budget of Owens Valley (Box E). It has been difficult, however, to synthesize local analyses into regional and national pictures. Regional and national analyses of water-cycle components could be accomplished more effectively through a coordinated national initiative such as the assessment described in this report.



What is a water budget?

Hydrologists use water budgets to account for flow and storage changes in natural systems that contain water. Systems of interest can be features such as rivers, lakes, drainage basins, the land surface, or aquifers. Water budgets for each of these systems use the relation:

(WATER INFLOW)–(WATER OUTFLOW)=(CHANGE IN WATER STORAGE)

Typical water budget components

WATER INFLOW

- **—Precipitation**
- **—Surface-water flow into basin**
- **— Imported water**
- **—Ground-water inflow**

WATER OUTFLOW

- **—Evaporation**
- **—Transpiration by vegetation (evapotranspiration)**
- **—Surface-water outflow**
- **—Exported water**
- **—Ground-water outflow**

CHANGE IN WATER STORAGE, increased/decreased water in:

- **—Snowpack**
- **—Unsaturated soil zone**
- **—Streams, rivers, reservoirs**
- **—Aquifers**

Figure 8. *Water-cycle components and simplified water budget of a drainage basin.*

D

Water Supply and Dry Rivers in the Humid East—Modeling the Effects of Water Withdrawals on Streamflow in the Ipswich River Basin, Massachusetts

Water shortages, dry riverbeds, and impaired stream habitats are most often associated with the arid West. Yet with increasing regularity, these water-resource issues are making headlines in the humid East. Water withdrawals for domestic, commercial, and other uses in the Ipswich River Basin in northeastern Massachusetts (fig. D–1), for example, frequently cause streamflows in the upper one-third of the basin to become very low or to cease completely during the summer, which results in sections of dry riverbed. Reduced streamflows stress aquatic communities, cause fish and mussel kills during dry years, and limit the value of the river as a biological, recreational, and scenic resource.

Recognizing that solutions to the basin's water-resource problems require cooperation among the many stakeholders, the Ipswich River Task Force was formed in 1996 to address water-resource issues in the basin. The Task Force determined that a watershed model was needed to serve as a basis for water-resources-management decisions in the basin. The following year, the USGS, in cooperation with the Massachusetts Departments of Environmental Management and Environmental Protection, began development and testing of such a model to determine the effects of water-use and land-use patterns on streamflow in the basin (Zarriello and Ries, 2000). Results of the model indicate that ground-water withdrawals substantially decrease streamflows during periods of low flow. For example, the model estimated that because of ground-water withdrawals, the Ipswich River ceases to flow at the site shown in the photographs below during some low-flow periods; without such withdrawals, the river would maintain a minimum flow of about 2.5 million gallons per day.

The model is a dynamic tool that continues to be applied to water-related issues in the basin. Most recently, the model was used to determine streamflows at sites along the main stem of the Ipswich River that were identified in a related study to be critical for fish passage during low flows (Armstrong and others, 2001). Model simulations were required because natural (unregulated) flow conditions are unknown at these sites. Results of the modeling and stream-habitat studies are currently being used by the Massachusetts Department of Environmental Protection to help establish withdrawal limits for water-supply wells, and are the cornerstone of a comprehensive watershed management plan being developed for the basin.

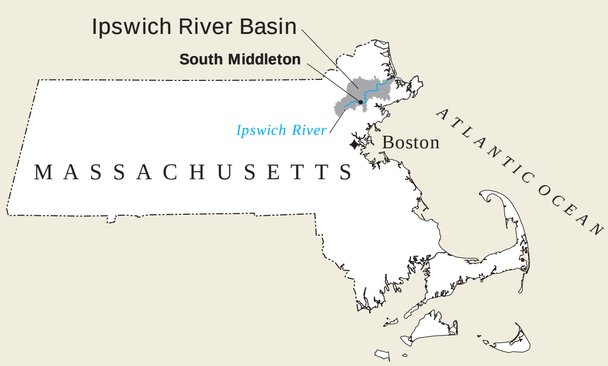


__Figure D–1.__ View of the Ipswich River near South Middleton, Massachusetts, during normal streamflow (left) and during the summer drought of 1999 (right). Figures modified from Zarriello and Ries, 2000. Photographs by David Armstrong and Timothy Driskell.

E

Cooperative Science Helps Determine Water Availability in Southern California

Owens Valley, a long narrow valley along the eastern flank of the Sierra Nevada in east-central California, is the main source of water for the City of Los Angeles. Diversion of streamflow for irrigation in the early 1900's and to the Owens River–Los Angeles Aqueduct after 1913 greatly altered the water budget of the valley. In 1970, a second pipeline to Los Angeles was completed, thereby increasing the capacity for exporting water. The additional water for Los Angeles was obtained by increasing surface-water diversions, by reducing irrigation, and by pumping ground water. As a result, ground-water levels were lowered, and native plants dependent on shallow ground water declined over large areas of the valley. The concern of residents that the additional export of water was degrading the environment of Owens Valley prompted lawsuits against Los Angeles. A clear, authoritative, and unbiased assessment of water availability in the valley was needed to settle the developing controversy.

Consequently, the USGS was approached by Inyo County and the City of Los Angeles and in the early 1980's began cooperative studies with them to evaluate the geology, water resources, and native vegetation of the valley. Hydrologic field investigations included innovative measurements of evapotranspiration, and simulations with a new valley-wide ground-water-flow model examined historical, current, and future water budgets for Owens Valley (Danskin, 1998). These USGS studies documented large decreases in evapotranspiration and springflows in response to water management in the 1970's and 1980's (fig. E–1) and projected even larger possible decreases in the future. As described in the settlement documents to pending lawsuits, the USGS studies "became the technical foundation for the joint long-term ground-water management plan" between Los Angeles and Inyo County, an operational plan designed to avoid long-term ground-water mining and the resultant adverse effects on native vegetation.

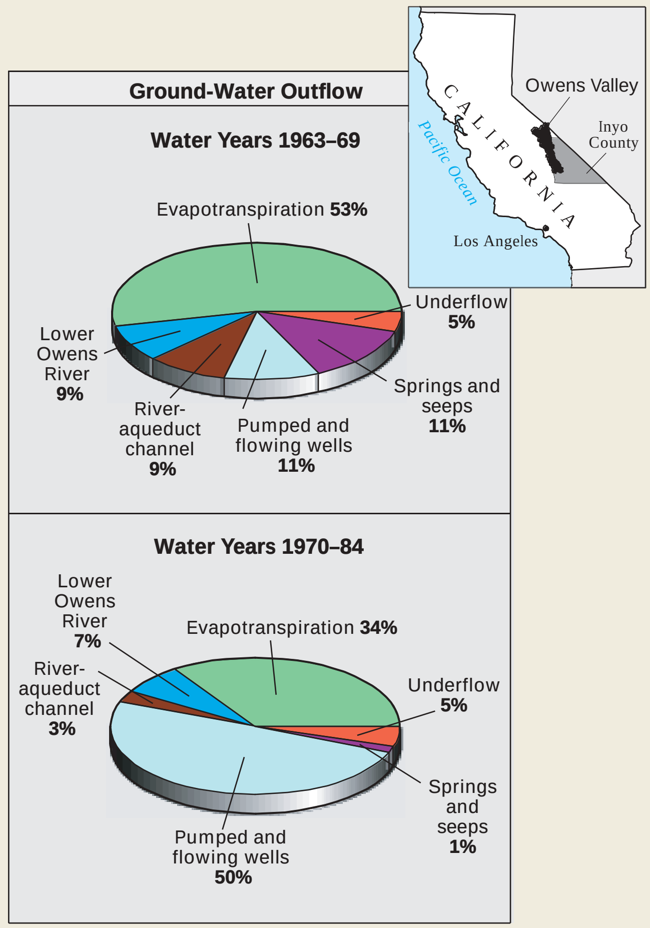


Figure E–1. *Simulated outflow components of the ground-water budget for Owens Valley for water years 1963–69 (prior to completion of the second Los Angeles aqueduct) and water years 1970–84 (during the initial operation of that aqueduct), showing large declines in evapotranspiration and springflow in response to large increases in ground-water pumpage (figure modified from Danskin, 1998).*

SUMMARY

In response to a directive from Congress, this report describes concepts for a national assessment of freshwater availability and use. The assessment would develop and report on indicators of the status and trends in storage volumes, flow rates, and uses of water nationwide. Currently, this information is not available in an up-to-date, nationally comprehensive and integrated form. The development and reporting of national indicators of water availability and use would be analogous to the task of other Federal statistical programs that produce and regularly update indicator variables that describe economic, demographic, and health conditions of the Nation. The effort to develop indicators should comply with the Office of Management and Budget Information Quality Guidelines. The assessment also would provide regional information on recharge, evapotranspiration, interbasin transfers, and other components of the water cycle across the country. This regional information would support analyses of water availability that are undertaken by many agencies nationwide and would benefit research quantifying variability and changes in the national and global water cycle.

The assessment would use basic hydrologic data collected by the USGS and by others to create the indicator variables. This process of computing indicators from the basic data would help to elucidate uncertainties in our knowledge of the Nation's hydrologic conditions. Data gaps identified by the program would provide useful feedback to the design of the data-collection networks. Thus, the assessment should influence basic-data programs by showing where uncertainty is greatest. Improved networks for the collection of surface-water and ground-water data are defined by USGS plans for the National Streamflow Information Program (U.S. Geological Survey, 1998a and 1999) and the Ground-Water Resources Program (U.S. Geological Survey, 1998b), and as part of the Cooperative Water Program. Water-use information developed by the program would expand upon and strengthen existing water-use efforts along the lines suggested by the National Research Council (2002).

The timeframe over which the indicators could become available would vary with the type of indicator. Surface-water indicators could be developed in a preliminary way over about a year's time. A year or more would be required to inventory existing data relevant to ground-water indicators and to determine appropriate ways to synthesize these data prior to development of the indicators. Several years would be required to develop improved approaches for estimating the water-use indicators prior to their implementation. The estimation of water-cycle components could be done in a stepwise basis over multiple years, depending on the scale of the effort.

The assessment should be highly collaborative, involving many Federal and State agencies, universities, and non-governmental interests. Collaboration across agency boundaries would ensure that information produced by the assessment could be aggregated with other types of physical, social, economic, and environmental data that affect water availability. These data include water-quality conditions, population statistics, land uses, water costs and pricing, climate data, and instream-flow requirements for aquatic habitats. To maximize the utility of the information, the design and development of the assessment should be coordinated through the Federal Advisory Committee on Water Information.

ACKNOWLEDGMENTS

U.S. Geological Survey contributors to this report included Robert M. Hirsch, William M. Alley, Paul M. Barlow, Michael D. Dettinger, W. Scott Gain, Pixie A. Hamilton, Susan S. Hutson, William H. Kirby, Leonard F. Konikow, Stanley A. Leake, Harry F. Lins, Molly A. Maupin, John E. Schefter, Gregory E. Schwarz, James R. Slack, and Gregg J. Wiche. Joy Monson and Margo VanAlstine prepared the final manuscript and illustrations.

REFERENCES CITED

Armstrong, D.S., Richards, T.A., and Parker, G.W., 2001, Assessment of habitat, fish communities, and streamflow requirements for habitat protection, Ipswich River, Massachusetts, 1998–99: U.S. Geological Survey Water-Resources Investigations Report 01–4161, 72 p.

Danskin, W.R., 1998, Evaluation of the hydrologic system and selected water-management alternatives in the Owens Valley, California: U.S. Geological Survey Water-Supply Paper 2370, 175 p.

Frederick, K.D., and Schwarz, G.E., 1999, Socioeconomic impacts of climate change on U.S. water supplies: Journal of the American Water Resources Association, v. 35, no. 6, p. 1563–1583.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, 604 p.

Hornberger, G.M., Aber, J.D., Bahr, J., Bales, R.C., Beven, K., Foufoula-Georgiou, E., Katul, G., Kinter, J.L., III, Koster, R.D., Lettenmaier, D.P., McKnight, D., Miller, K., Mitchell, K., Roads, J.O., Scanlon, B.R., and Smith, E., 2001, A plan for a new science initiative on the global water cycle: Washington, DC, U.S. Global Change Research Program, 118 p.

McGuire, V.L., and Sharpe, J.B., 1997, Water-level changes in the High Plains aquifer—Predevelopment to 1995: U.S. Geological Survey Water-Resources Investigations Report 97–4081, 2 pl.

McPherson, B.F., and Halley, Robert, 1996, The South Florida environment—A region under stress: U.S. Geological Survey Circular 1134, 61 p.

McPherson, B.F., Miller, R.L., Haag, K.H., and Bradner, Anne, 2000, Water quality in southern Florida, 1996–1998: U.S. Geological Survey Circular 1207, 32 p.

National Research Council, 2001, Envisioning the agenda for water resources research in the twenty-first century: Washington, DC, National Academy Press, 61 p.

______2002, Estimating water use in the United States—A new paradigm for the National Water Use Information Program: Washington, DC, National Academy Press.

Osborn, C.T., and Shabman, Leonard, 1988, The use of water resource information—The second national assessment: Water Resources Bulletin, v. 24, no. 6, p.1161–1167.

Ruddy, B.C., and Hitt, K.J., 1990, Summary of selected characteristics of large reservoirs in the United States and Puerto Rico, 1988: U.S. Geological Survey Open-File Report 90–163, 295 p.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L., 1987, Hydrologic unit maps: U.S. Geological Survey Water-Supply Paper 2294, 63 p.

Solley, W.B., 1998, Estimates of water use in the western United States in 1990, and water-use trends, 1960–90: U.S. Geological Survey Open-File Report 97–176, 15 p.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p.

Stallard, R.F., 1998, Terrestrial sedimentation and the carbon cycle—Coupling weathering and erosion to carbon burial: Global Biogeochemical Cycles, v. 12, no. 2, p. 231–257.

Stallard, R.F., Mixon, D., Kinner, D.A., and Worstell, B., 2001, RESIS–II—Making the reservoir survey system complete and user friendly, *in* Proceedings of the Seventh Federal Interagency Sedimentation Conference: Reno, Nevada, Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation, v. 2, p. IX9–IX11.

Steffen, L.J., 1996, A reservoir sedimentation survey information system—RESIS, *in* Proceedings of the Sixth Federal Interagency Sedimentation Conference: Las Vegas, Nevada, Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation, p. 29–37.

Taylor, C.J., and Alley, W.M., 2002, Ground-water-level monitoring and the importance of long-term water-level data: U.S. Geological Survey Circular 1217, 68 p.

U.S. Army Corps of Engineers, 2001, National inventory of dams: accessed September 26, 2001, at URL http://crunch.tec.army.mil/nid/webpages/nid.cfm

U.S. Geological Survey, 1982, A U.S. Geological Survey data standard, codes for the identification of hydrologic units in the United States and the Caribbean outlying areas: U.S. Geological Survey Circular 878–A, 115 p.

______1984, National water summary 1983—Hydrologic events and issues: U.S. Geological Survey Water-Supply Paper 2250, 243 p.

______1998a, A new evaluation of the USGS streamgaging network: U.S. Geological Survey Report to Congress, November 30, 1998, 20 p.

______1998b, Strategic directions for the U.S. Geological Survey Ground-Water Resources Program: U.S. Geological Survey Report to Congress, November 30, 1998, 14 p.

______1999, Streamflow information for the next century—A plan for the National Streamflow Information Program of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 99–456, 13 p.

______2001, Map of real-time streamflow: accessed December 5, 2001, at URL http://water.usgs.gov/waterwatch/

U.S. Water Resources Council, 1968, The Nation's water resources: Washington, DC, U.S. Government Printing Office.

______1978, The Nation's water resources 1975–2000, Second National Water Assessment: Washington, DC, U.S. Government Printing Office.

Zarriello, P.J., and Ries, K.G. III, 2000, A precipitation-runoff model for the analysis of the effects of water withdrawals on streamflow, Ipswich River Basin, Massachusetts: U.S. Geological Survey Water-Resources Investigation Report 00–4029, 99 p.

APPENDIX A

List Of Individuals Providing Input To This Report

We thank individuals and organizations listed below who responded to our solicitation for input on a plan for a national assessment of water availability and use.

State Agencies and Organizations

Barney Austin, Texas Water Development Board, Austin, TX
William Turner, New Mexico Office of Natural Resources Trustee, Albuquerque, NM
Rhea Graham, New Mexico Interstate Stream Commission, Albuquerque, NM
Larry Anderson, Utah Department of Natural Resources, Division of Water Resources, Salt Lake City, UT
Don Ostler, Utah Department of Environmental Quality, Division of Water Quality, Salt Lake City, UT
Karl Muessig, Office of the State Geologist, New Jersey Geological Survey, Trenton, NJ
Marcia Willhite, Bureau of Water, Illinois Environmental Protection Agency, Springfield, IL
Richard Cobb, Bureau of Water, Illinois Environmental Protection Agency, Springfield, IL
William Compton, Illinois Governor's Groundwater Advisory Council, Springfield, IL
Derek Winstanley, Illinois State Water Survey, Champaign, IL
David Hamilton, Surface Water Quality Division, Michigan Department of Environmental Quality, Lansing, MI
Mimi Garstang, Geological Survey and Resource Assessment Division, Missouri Department of Natural Resources, Rolla, MO
Rodney DeHan, Florida Geological Survey, Tallahassee, FL

Federal Agencies and Organizations

Henry Diaz, Climate Diagnostics Center, National Oceanic and Atmospheric Administration, Boulder, CO
Robert Webb, Climate Diagnostics Center, National Oceanic and Atmospheric Administration, Boulder, CO
Donald Scavia, National Ocean Service and National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, Silver Spring, MD
Kathy Jacobs, Office of Global Programs, National Oceanic and Atmospheric Administration, Silver Spring, MD
Richard Lawford, Office of Global Programs, National Oceanic and Atmospheric Administration, Silver Spring, MD
Robert Kripowicz, Office of Fossil Energy, U.S. Department of Energy, Washington, DC
Thomas Feeley III, National Energy Technology Laboratory, U.S. Department of Energy, Pittsburgh, PA
Terry Ackman, National Energy Technology Laboratory, U.S. Department of Energy, Pittsburgh, PA
David Beecy, Office of Fossil Energy, U.S. Department of Energy, Washington, DC
Randy Pennington, Office of Fossil Energy, U.S. Department of Energy, Germantown, MD
Reid Goforth, Office of Research Coordination, U.S. Fish and Wildlife Service, Arlington, VA
Theodore Heintz, Office of Policy Analysis, U.S. Department of the Interior, Washington, DC
Sidney Eugene Gibson, Tennessee Valley Authority, Knoxville, TN
Janet Herrin, Tennessee Valley Authority, Knoxville, TN
Katherine Smith, Economic Research Service, U.S. Department of Agriculture, Washington, DC
Tim Smith, U.S. Interagency Working Group on Sustainable Development Indicators, Washington, DC
David Berry, U.S. Interagency Working Group on Sustainable Development Indicators, Washington, DC
Kevin Whalen, Bureau of Land Management, Washington, DC
Shannon Cunniff, Bureau of Reclamation, Washington, DC
Donald Ralston, Bureau of Reclamation, Washington, DC
David Wingerd, U.S. Army Corps of Engineers, Washington, DC
Dan Kimball, National Park Service, Fort Collins, CO
Sharon Kliwinski, National Park Service, Washington, DC

Universities

David Maidment, Department of Civil Engineering, The University of Texas, Austin, TX
Roger Bales, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ
Richard Luthy, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA
Dara Entekhabi, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA
Richard Vogel, Department of Civil and Environmental Engineering, Tufts University, Medford, MA
Paul Kirshen, Department of Civil and Environmental Engineering, Tufts University, Medford, MA
Donald Siegel, Department of Earth Sciences, Syracuse University, Syracuse, NY
Leonard Shabman, Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, VA
Robert Ward, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO
Gary Johnson, Department of Geological Sciences, University of Idaho, Idaho Falls, ID
Thomas Harter, Department of Land, Air and Water Resources and Kearney Agricultural Center, University of California, Davis, CA
Neil Grigg, Department of Civil Engineering, Colorado State University, Fort Collins, CO
Richard Sparks, Illinois Water Resources Center, University of Illinois, Urbana, IL
William McDowell, New Hampshire Water Resources Research Center, Department of Natural Resources, University of New Hampshire, Durham, NH
Kenneth Steele, Department of Geosciences, University of Arkansas, Fayetteville, AR
Henry Vaux, University of California, Division of Agriculture and Natural Resources, Oakland, CA
Charles Turner, Department of Civil Engineering, University of Texas, El Paso, TX
Jeffery Ballweber, Water Resources Research Institute, Mississippi State University, Mississippi State, MS
Charles Howe, Institute of Behavioral Science, University of Colorado, Boulder, CO
S. Lawrence Dingman, Earth Sciences Department, University of New Hampshire, Durham, NH

Other Individuals and Organizations

Gerald Galloway, International Joint Commission, Washington, DC
William Nuttle, Consultant and Member of National Research Council Committee on Hydrological Sciences, Ontario, Canada
Robert Goldstein, Electric Power Research Institute, Palo Alto, CA
National Research Council Committee on Hydrologic Science, Washington, DC
National Research Council Committee on Water Resources, Washington, DC
Western States Water Council, Midvale, UT
William Horvath, National Association of Conservation Districts, Stevens Point, WI
Susan Seacrest, The Groundwater Foundation, Lincoln, NE
Thomas Curtis, American Water Works Association, Washington, DC
Stephen Ragone, National Ground Water Association, Reston, VA
Susan Gilson, Interstate Council on Water Policy, Washington, DC
Robert Hughes, American Fisheries Society, Corvallis, OR
Ghassan Rassam, American Fisheries Society, Bethesda, MD
Robin O'Malley, The H. John Heinz III Center for Science, Economics and the Environment, Washington, DC
Barry Norris, Association of Western State Engineers, Salem, OR
S. Elizabeth Birnbaum, American Rivers, Washington, DC
Linda Mather Walker, League of Women Voters, New Orleans, LA
Betsy Cody, Congressional Research Service, Washington, DC
Claudia Copeland, Congressional Research Service, Washington, DC
Mary Tiemann, Congressional Research Service, Washington, DC
Jeff Zinn, Congressional Research Service, Washington, DC

USGS

Concepts for National Assessment of Water Availability and Use

Circular 1223

ISBN 0-607-98593-3

9 780607 985930

Printed on recycled paper