Water Availability for the Western United States—*Key Scientific Challenges*

By Mark T. Anderson and Lloyd H. Woosley, Jr.

Circular 1261

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2005

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Suggested citation:
Anderson, Mark T., and Woosley, Lloyd H., Jr., 2005, Water availability for the Western United States—Key scientific challenges: U.S. Geological Survey Circular 1261, 85 p.

Library of Congress Cataloging-in-Publication Data

Anderson, Mark T. (Mark Theodore), 1952-
Water availability for the western United States : key scientific challenges / by Mark T. Anderson and Lloyd H. Woosley, Jr.
p. cm. -- (Circular ; 1261)
Includes bibliographic references.
ISBN 0-607-95585-6 (alk. paper)
1. Water quality management--West (U.S.) 2. Water consumption--West (U.S.) 3. Water-supply--West (U.S.) I. Woosley, Lloyd H. II. Title. III. U.S. Geological Survey circular ; 1261-G.

TD223.6.A54 2003
363’.6’1’0978--dc22

2003064311

Foreword

A constant and assured supply of fresh water is critical to sustain ourselves, our communities, and our Nation. While true, this traditional approach, that water is for human use, is no longer sufficient. As society's values have changed over time, water availability now includes the demand to sustain natural ecosystems as well as providing the water needed to sustain economic activity. This report discusses how the role and priorities for science to support effective water management are changing.

The challenges facing water managers continue to mount, especially in the West. Such factors as a demographic shift in our population, climate variability (including the potential for severe sustained droughts), climate change, water-rights issues, depletion of ground water in storage, introduction of new water storage and water-use technologies, and protection of endangered species, add to a growing complexity for management. These and other factors are discussed and given some context in this report. Resource managers that work in this complex environment are asking more of science today to support and improve their decisionmaking. The key challenges for science, in response to these demands, are discussed and include case examples in this report. In some instances, the conduct of science to support water-resource management is bringing about a new and more integrated role for the science of the U.S. Geological Survey. The purpose of this report is to broaden the understanding of Western water availability, the modern role for science, and the value of monitoring and research to ensure an adequate water supply for the Nation's future.

Robert M. Hirsch
Associate Director for Water

Acknowledgments

The authors gratefully acknowledge the assistance of numerous agencies and individuals who contributed ideas, data, illustrations, and photographs to this report. The Bureau of Reclamation (BOR) and the U.S. Army Corps of Engineers provided the reservoir contents data. The National Oceanic and Atmospheric Administration (NOAA) provided data and analysis on temperature and precipitation with special thanks to Jay Lawrimore, Trevor Wallis, and Andy Goss. The Arizona Department of Water Resources and Tucson Water supplied data on water use and artificial recharge. The authors thank many of our colleagues for their vision and input to early drafts of this report: Peter W. Anttila, Marc A. Sylvester, Keith R. Prince, John M. Klein, Nick B. Melcher, and Linda J. Britton.

The authors thank the many reviewers who provided input or made constructive suggestions to improve the report: Stanley A. Leake, William M. Alley, Harry F. Lins, Donald R. Pool, Robert M. Hirsch, Keith G. Kirk, Dennis D. Lynch, Robert H. Webb, Jim E. Monical, Alice D. Konieczki, Gregory J. McCabe, Michael Dettinger, Gail E. Cordy, Virginia L. McGuire, Daniel G. Driscoll, Matthew Roop, Kenneth J. Hollett. We especially appreciate the technical assistance of our colleagues on the case study examples: James R. Bartolino, Devin L. Galloway, James M. Leenhouts, Eric G. Reichard, and John C. Risley. The authors thank several colleagues for their formal review of the whole manuscript: Dennis G. Woodward, John C. Risley, and George Garklavs. Robert J. Glennon (University of Arizona) provided guidance on the water-rights discussion for which we are grateful. We thank the many photographers who graciously agreed to allow us to present their work in this report in return for mere attribution of their photographs. Illustrations for the report were prepared by John L. Callahan and Margo J. VanAlstine. The cover was prepared by Sidney H. Alwin. Steve A. Longsworth and Tracey L. Suzuki edited early versions of the manuscript. Carol L. Anderson edited the final manuscript, and Joy K. Monson prepared the final manuscript for publication. Carla S. Anderson provided research and editorial support throughout the entire report preparation process.

Contents

Boxes

Figures

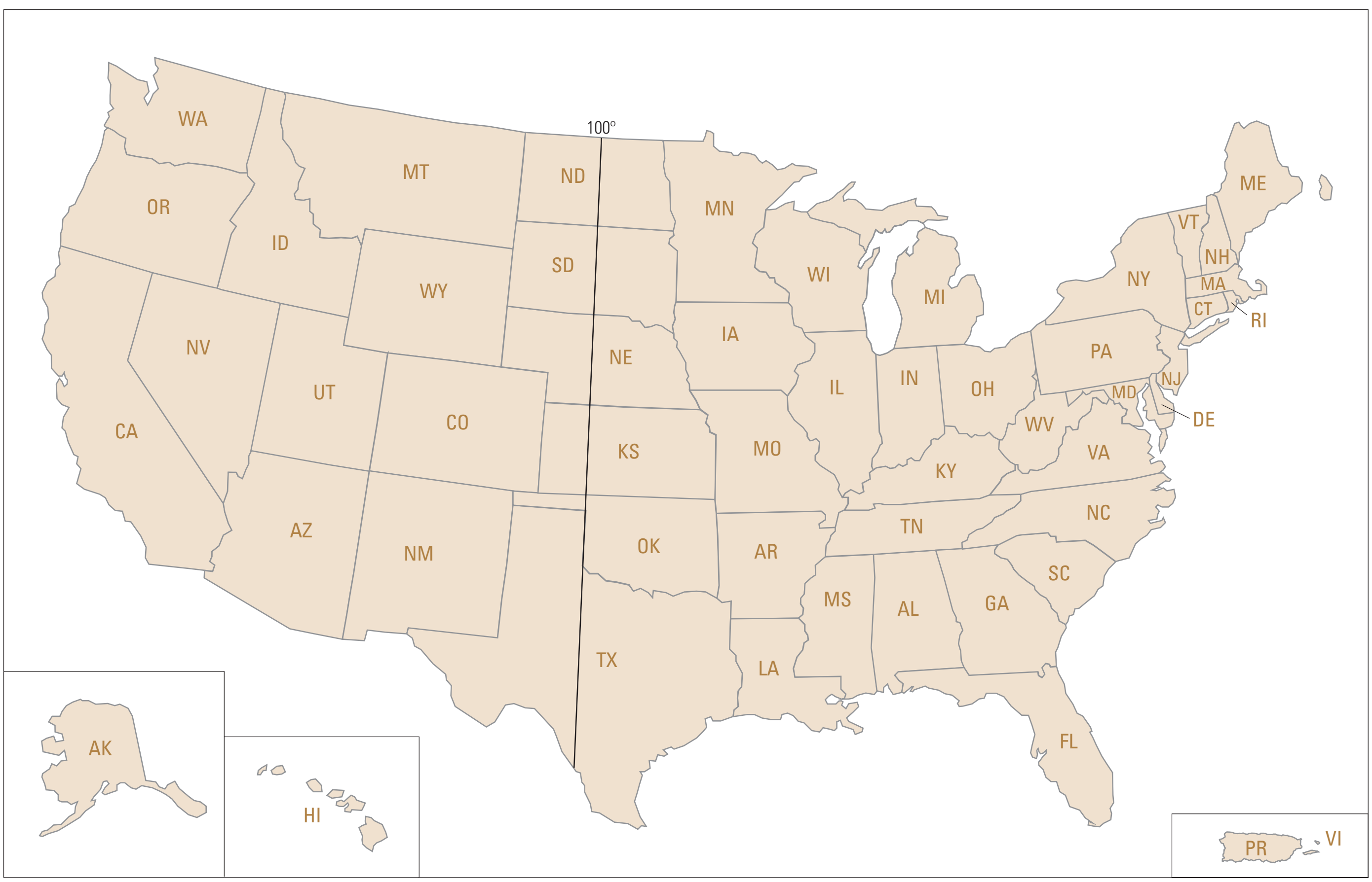
Tables

Sockeye salmon migrating upstream to spawn, Hansen Creek, Alaska. (Photograph courtesy of Thomas P. Quinn, School of Aquatic and Fishery Sciences, University of Washington, Seattle.)

Water Availability for the Western United States—*Key Scientific Challenges*

Abstract

In the Western United States, the availability of water has become a serious concern for many communities and rural areas. Near population centers, surface-water supplies are fully appropriated, and many communities are dependent upon ground water drawn from storage, which is an unsustainable strategy. Water of acceptable quality is increasingly hard to find because local sources are allocated to prior uses, depleted by overpumping, or diminished by drought stress. Some of the inherent characteristics of the West add complexity to the task of securing water supplies. The Western States, including the arid Southwest, have the most rapid population growth in the United States. The climate varies widely in the West, but it is best known for its low precipitation, aridity, and drought. There is evidence that the climate is warming, which will have consequences for Western water supplies, such as increased minimum streamflow and earlier snowmelt events in snow-dominated basins. The potential for departures from average climatic conditions threatens to disrupt society and local to regional economies. The appropriative rights doctrine governs the management of water in most Western States, although some aspects of the riparian doctrine are being incorporated. The "use it or lose it" provisions of Western water law discourage conservation and make the reallocation of water to instream environmental uses more difficult. The hydrologic sciences have defined the interconnectedness



of ground water and surface water, yet these resources are still administered separately by most States. The definition of water availability has been expanded to include sustaining riparian ecosystems and individual endangered species, which are disproportionately represented in the Western States. Federal reserved rights, common in the West because of the large amount of Federal land, exist with quite senior priority dates whether or not water is currently being used. A major challenge for water users in the West is that these reserved rights may supersede other existing users. The minimum amount of water required, however, to sustain native peoples, a riparian system, or an endangered species eventually will need to be known in order to manage the available water supply. Periodic inventory and assessment of the amounts and trends of water available in surface water and ground water are needed to support water management. There is a widespread perception that the amount of available water is diminishing with time. This and other perceptions about water availability should be replaced by objective data and analysis. Some data are presented here for the major Western rivers that show that flows are not decreasing in most streams and rivers in the West. Systematic information is lacking to make broad assessments of ground-water availability, but available data for specific aquifers indicate that these aquifers are being depleted, especially near population centers.

The complexity added to the issue of Western water availability by these and other factors gives rise to a significant role of science. Science has played a role in support of Western water development from the beginning, and the role has evolved and changed over time as society's values have changed. In this report, the role of science is discussed in three phases: (1) development and construction, (2) consequences and environmental awareness, and (3) sustainability. The development and construction phase includes some historical accounting of water development in the West and shows how some precedents set in those early days are still applied today. Science has played an important role in the second phase by objectively pointing out the consequences of this development and construction phase, such as the effects from converting rivers to reservoirs, the effects of ground-water pumping on surface water in streams, land-surface subsidence, and the changes in water quality brought about by the disposal of wastewater and manmade chemicals into the Nation's waterways and aquifers. The sustainability phase reflects the present efforts of water managers and other natural-resource managers to sustain water supplies beyond the present generation. Sustainability, as presently interpreted, goes beyond mere water availability for water supply, and includes ecosystems and even individual species. Sustainability by this definition is superficially appealing, but is and will continue to be a significant challenge for science to translate into measurable water-management strategies. A sustainable water supply for a community ideally would provide enough water to support a growing population and economy, even during protracted periods of drought—a tall order. There are many scientific challenges surrounding a sustainable use of water resources, but five key challenges are discussed in this report: (1) the determination of a sustainable level of ground-water use that meets identified management needs, (2) artificial recharge in the long-term, (3) selected water-use strategies such as desalination and water reuse, (4) sustaining valued ecosystems, and (5) sustaining individual endangered species. These key challenges will demand scientific attention in the coming decades and are examined here in detail, including the following case examples: (1) the Middle Rio Grande Basin, New Mexico; (2) artificial recharge in the Greater Los Angeles, California, area; (3) selected water-use strategies (no location); (4) San Pedro Riparian National Conservation area, Arizona; and (5) Upper Klamath Lake, Oregon. The case examples illustrate the technical and scientific complexity of the issues and explain the scientific approaches taken to address these issues, including the types and amounts of data collected. To support society's demand for sustainability, scientists, managers, policymakers and water users at large will need to develop, communicate, and use scientific information in more effective ways. New collaborative ways of conducting monitoring and research across disciplinary lines will be needed to develop quantitative habitat requirements for ecosystems and endangered species. The new role of science will be to support environmental decisionmaking to achieve some new level of sustainable use that will provide an assured supply of good-quality water for humans and for stream and riparian ecosystems.

Introduction

Water availability is a major issue in the Western United States. Recent drought conditions in much of the West have brought urgency to this issue for water-resource managers, policymakers, and the public. An assured supply of good-quality water is essential for public and ecosystem health, community stability, and economic growth. Humans require only 0.5 gallon per person per day for survival (National Academy of Sciences, 1977; Gleick, 1996). In the United States, however, water use averages about 150 gallons per person per day for domestic and municipal purposes, and an additional 1,300 gallons per person per day for agriculture and industry (Solley and others, 1998). Will there be sufficient freshwater resources in the future to sustain communities, economic growth, and quality of life?

Water supply and management issues are becoming increasingly important as pressure on existing supplies continues to grow. Increasing populations in many areas, combined with increasing demand for water for recreation, scenic value, and fish and wildlife habitat, have resulted in conflicts throughout the country, especially in the arid West (Cody and Hughes, 2003).

In the American West, the task of securing water supplies without adverse effect to the environment has become a daunting challenge that is accentuated during times of drought. Water of acceptable quality is becoming harder to find because local sources are allocated to prior uses, depleted by overuse, or diminished by drought stress. For Williams, Arizona, a small community near the Grand Canyon, the situation became desperate in the late 1990s as the municipal reservoirs dried up one by one. Large cities are not immune to water-supply shortages. Albuquerque, New Mexico; El Paso, Texas; Las Vegas, Nevada; and Tucson, Arizona, for example, cannot supply their burgeoning growth from present sources.

Water availability traditionally has meant securing a volume of water to meet a current and projected demand on the basis of existing and projected usage. An added challenge today for water- and natural-resource managers is that water is expected to be available for nonextractive uses, such as maintaining ground-water levels beneath riparian areas, preventing freshwater-saltwater interfaces from migrating landward, maintaining flows and water temperatures to support fishery needs, or restoring flooding to dammed rivers—all uses requiring prescriptions for which there is little historical precedent or experience.

Many factors beyond the obvious aridity make securing water supplies in the West challenging. A demographic shift is occurring in the population of the United States, and people are migrating in record numbers to the West—especially the Southwest, the most arid region of the continent. Aquifers near many population centers are fully developed and, in some cases, being rapidly depleted. Many people and communities in the Southwest are dependent upon water drawn from ground-water storage, which cannot be sustained in the long term. Surface water often is fully appropriated, yet water managers are forced to sustain instream flows on some streams and rivers to comply with the Endangered Species Act (ESA). Western water law, or the prior appropriation doctrine, in the past discouraged conservation and constrained the reallocation of water among beneficial uses. Western water law is now undergoing significant revision in some States and under this contemporary doctrine, it is possible to sell a portion of water conserved to third parties. Furthermore, the body of water law and administrative rules that govern the management of water in most Western States treat surface water and ground water separately, in opposition to hydrologic reality. The amount of water used by the average household in the West has decreased somewhat since 1985, but still exceeds the national average (Solley and others, 1998).

The supportive role of science has changed over time as water development has progressed and society's values have shifted. The role for science is discussed in three phases: (1) development and construction, (2) consequences and environmental awareness, and (3) sustainability. The amount and complexity of data increase in successive phases of development and management. For example, there is an awareness that surface water and ground water are in hydrologic connection, which suggests a more holistic management approach may be needed. This awareness is relatively recent, and the analytical tools necessary to construct unified water budgets and predictive models only now are being developed. To respond to society's call for sustainable use, science, represented by a wide range of disciplines, is being called upon to better quantify and monitor changes in the hydrologic system, to define the physical-habitat requirements of stream and riparian ecosystems, and to provide for the life-sustaining needs of individual species being affected or in danger of extinction.

Science plays an important role in the solution of issues by first raising the awareness that issues exist and, as alternative solutions are proposed, describing the potential hydrologic and environmental consequences. Science and technology cannot promise more water from undiscovered sources. Science, however, can offer more informed choices and provide a better understanding of the environmental consequences of those alternatives.

Purpose and Scope

This report examines water availability and the factors that complicate water management in the West—those States that lie, all or in part, west of the 100th Meridian (fig. 1). This report relies primarily on existing information, which is less extensive for Alaska and Hawaii and, therefore, focuses on the 17 Western States in the conterminous United States. Relevant water-availability information presented in the report, therefore, applies mainly to the contiguous Western United States. The report points out the need for scientific assessment of water availability for the West to support water management and examines the many characteristics of the American West that make the task of assessing and securing water a challenge. These characteristics and how they impinge upon and complicate the task of assessing water availability are examined to provide the context and role for science.

The supportive role of science has changed throughout history as water development has advanced. The types of scientific information useful to manage water resources is discussed as it has evolved from initially securing water supplies to achieving a balance between human and ecosystem needs. There are major scientific challenges facing the West, especially concerning society's desire to achieve sustainable water use. Sustainability is a concept that best describes the frequent refrain of water managers in the West today. It is not being proposed as a goal, but rather a response to society's current demands. For example, the sustainability of water is the management goal for the San Pedro River in southern Arizona, as expressed by Congress in recent legislation (P.L. 108–136) . These management decisions can be improved by considering the consequences of various water-use scenarios as difficult choices are presented to managers who are charged to resolve water-supply needs. These challenges are presented in this report, and the associated scientific information needs are examined through several case examples. This report focuses on the need for science in water-resources assessment and the importance of scientific information to support prudent water-resources management and policy. It presents some of the types of regional scale information useful for making assessments of water availability and use and examines the role of science in support of water management, irrespective of the level of government.

Previous Work

Much has been written on the subject of Western water, its complexity, and the growing tension about how to resolve long-standing and new conflicts. The Western Water Policy Review Act of 1992 (P.L. 102–575) directed the President to undertake a comprehensive review of Federal activities that directly or indirectly affect the allocation and use of water resources in the 19 Western States. The Western Water Policy Review Advisory Commission released its findings in a report entitled, "Water in the West: Challenge for the Next Century" (1998). The report reviews Federal policy and makes recommendations regarding Federal water programs. In an effort to graphically portray the changing patterns of the American West, the *Atlas of the New West* was prepared (Riebsame, 1997). Illustrations show the new forms of old Western battles over land and water, and changes due to many other factors such as urbanization.

Figure 1. *States west of the 100th Meridian. Photograph of 100th Meridian marker along Highway 14, near Blunt, South Dakota (1983), provided by Paul Starrs, Department of Geography, University of Nevada, Reno.*

At the request of Congress, the U.S. Geological Survey (USGS) prepared a report that describes the concepts for a national assessment of freshwater availability and use (Barlow and others, 2002). This report points out the lack of nationally comprehensive, consistent, and up-to-date data sets upon which to base assessments of water availability. These assessments would provide regional information on recharge, evapotranspiration, interbasin transfers, and other components of the water cycle across the country. These assessments would use basic hydrologic data collected by the USGS and others to create the simple indicators of water-resource conditions and trends. This process of computing indicators from the basic data would help to elucidate uncertainties about national hydrologic conditions (Barlow and others, 2002).

The U.S. Department of the Interior began a program, known as Water 2025, to help avert water crisis among competing water users in the West. Water 2025 establishes a framework to cooperatively address the challenges facing many Western communities because of explosive population growth, the emerging need for water for environmental and recreational uses, and the national importance of the domestic production of food and fiber from western farms and ranches. The program has identified specific areas where the potential for conflict is rated high by the year 2025. The program will use four key tools to avert crisis: (1) conservation, efficiency, and markets; (2) collaboration, (3) improved technology; and (4) removal of institutional barriers and increased interagency coordination. For more information on Water 2025, the reader is referred to U.S. Department of the Interior (*http://www.doi.gov/water2025/Water2025.pdf*).

Characteristics of the American West

The American West is different from the East in many ways: climate, rugged mountains, expansive plains with open horizons, vast Federal lands, native peoples and tribal lands, a unique history of settlement—and too little water. It has captivated the imaginations of people worldwide for more than 150 years and enticed them to come with high hopes for economic prosperity and a better life—for free land, gold for the taking, jobs, and the use of Federal lands for grazing cattle, harvesting timber, and extracting minerals. The availability of water determined the initial human settlement of the West, but technology has permitted cities and agricultural areas to grow unrestrained in the most arid regions. The early competition for water, whether for mining or for agriculture, gave rise to current patterns of water use and a unique system of water law. Many of these characteristics of the American West make the task of securing water challenging. How these characteristics impinge upon and complicate the task of assessing water availability is examined in the sections that follow. Furthermore, this context is provided to promote a better understanding of the need for science and the role it plays, which is presented later in the report.

Population Growth and Demographic Change

A steady demographic shift is occurring in the United States. According to the 2000 U.S. Census, about one-third or 91.5 million of the 281 million people in the United States now reside in the 17 Western States (fig. 1). These Western States accounted for 50 percent of the U.S. population growth from 1990 to 2000 (Perry and Mackun, 2001), and 7 of the 10 fastest growing States in the Nation are in the West (fig. 2). Projections for population growth in the Southwest are estimated to increase consistently as a proportion of the total U.S. population through 2030 (fig. 3; Campbell, 1996).

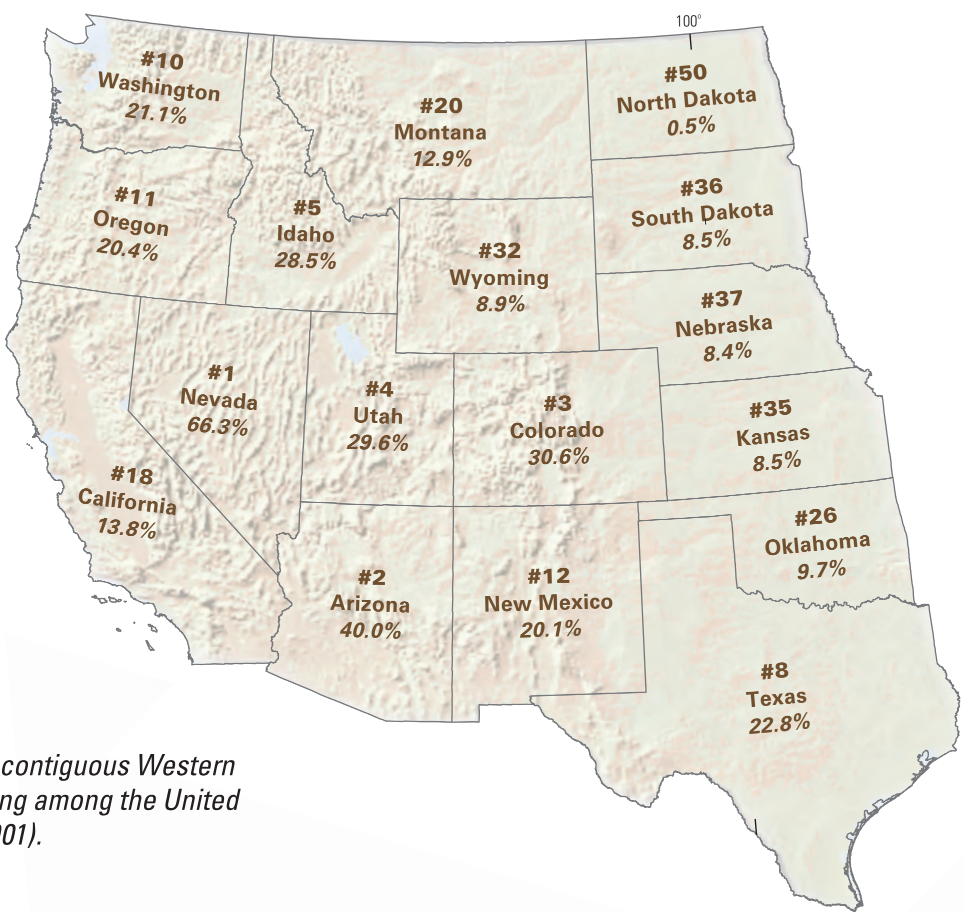


Figure 2. *Population growth of the contiguous Western States in percent and relative ranking among the United States. From Perry and Mackun (2001).*

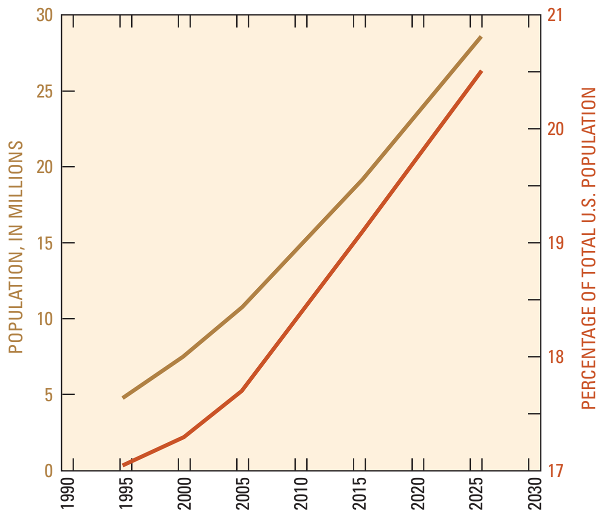


Figure 3. *Projection of population growth for the Southwestern United States. States include Arizona, California, Colorado, Nevada, New Mexico, and Utah. From Campbell (1996).*

Climate and Climate Change

The extremes of climate for the United States are found in the Western States from the hot and dry areas of the Mojave Desert in Death Valley, California, to the cold areas of the Rocky Mountains and wet areas of the Pacific Northwest. Large areas of the Western States, however, are characterized by low humidity, low precipitation, and warm to hot temperatures (figs. 4 and 5). The seasonal distribution of precipitation also distinguishes the West. A larger proportion of the annual precipitation falls in the winter months—in California, Oregon, and Washington (fig. 6).

The 100th Meridian has separated the West from the East ever since John Wesley Powell's classic report on the lands of this arid region (Powell, 1878). West of the 100th Meridian, rainfall is usually less than 20 inches per year, at least in the lowlands where people tended to settle—too little to grow crops without irrigation. The conditions of aridity still define the West and give many residents a preoccupation with water. Because of this aridity and an unfavorable distribution of water on the landscape, the availability of water has come to dominate natural-resource management and community stability, especially in times of shortage.

In the West, annual precipitation can vary greatly from year to year. Droughts reoccur with no known periodicity, but have shaped the history of the West and attitudes about water. Communities and local economies solely dependent upon surface water become especially vulnerable during periods of drought, which often stimulates well drilling to augment surface-water supplies with ground water.

The climate of the Northern Hemisphere is warming, but the consequences are not completely known (Intergovernmental Panel on Climate Change, 2001a). The evidence suggests that climatic regime shifts may occur rather precipitously on time scales of decades rather than slowly over centuries or millennia. The United Nations Intergovernmental Panel on Climate Change (2001a) reports that, after accounting for factors such as the heat island effect, global surface air temperatures rose an average of 0.6º Celsius during the 20th century and that 1998 was the warmest year in the instrumented record (fig. 7). Mean annual temperatures for some Western cities are increasing (fig. 8), but resolving whether these trends reflect global conditions or local conditions, such as the heat island effect, is beyond the scope of this report.

Some climate models predict that the atmosphere will continue to warm and that globally averaged surface temperatures will rise 1.4 to 5.8º Celsius from 1990 to 2100 (Intergovernmental Panel on Climate Change, 2001a). The evidence is persuasive that air temperatures are rising and that the atmosphere is warming, especially near the land surface. The important question is—What are the consequences for hydrology? A warmer atmosphere is capable of transporting more water from the oceans to the continents. This increased capability should be manifested by measurable increases of precipitation on land. For most sites in the West this has held true; precipitation has increased during the last century (fig. 9).

Climate models cannot be used to differentiate, with any degree of certainty, which regions of the United States will experience an increase in precipitation. Some regions may become drier as precipitation patterns shift, even though total precipitation on the continent has increased. Climate change is expected to result in an alteration in the timing and amount of runoff. A warmer climate will change the proportion of precipitation falling as snow and rain. The mountain snowpacks of the West serve as natural storage reservoirs that delay the release of runoff through the summer. Changes in these runoff patterns may complicate reservoir management. For further information about the potential consequences of climate change on the water resources of the United States, see the reports released under the aegis of the Global Climate Change Research Program (Merideth and others, 1998; Gleick and Adams, 2000). Taken collectively, the aforesaid factors have raised the complexity of water management to levels never experienced.

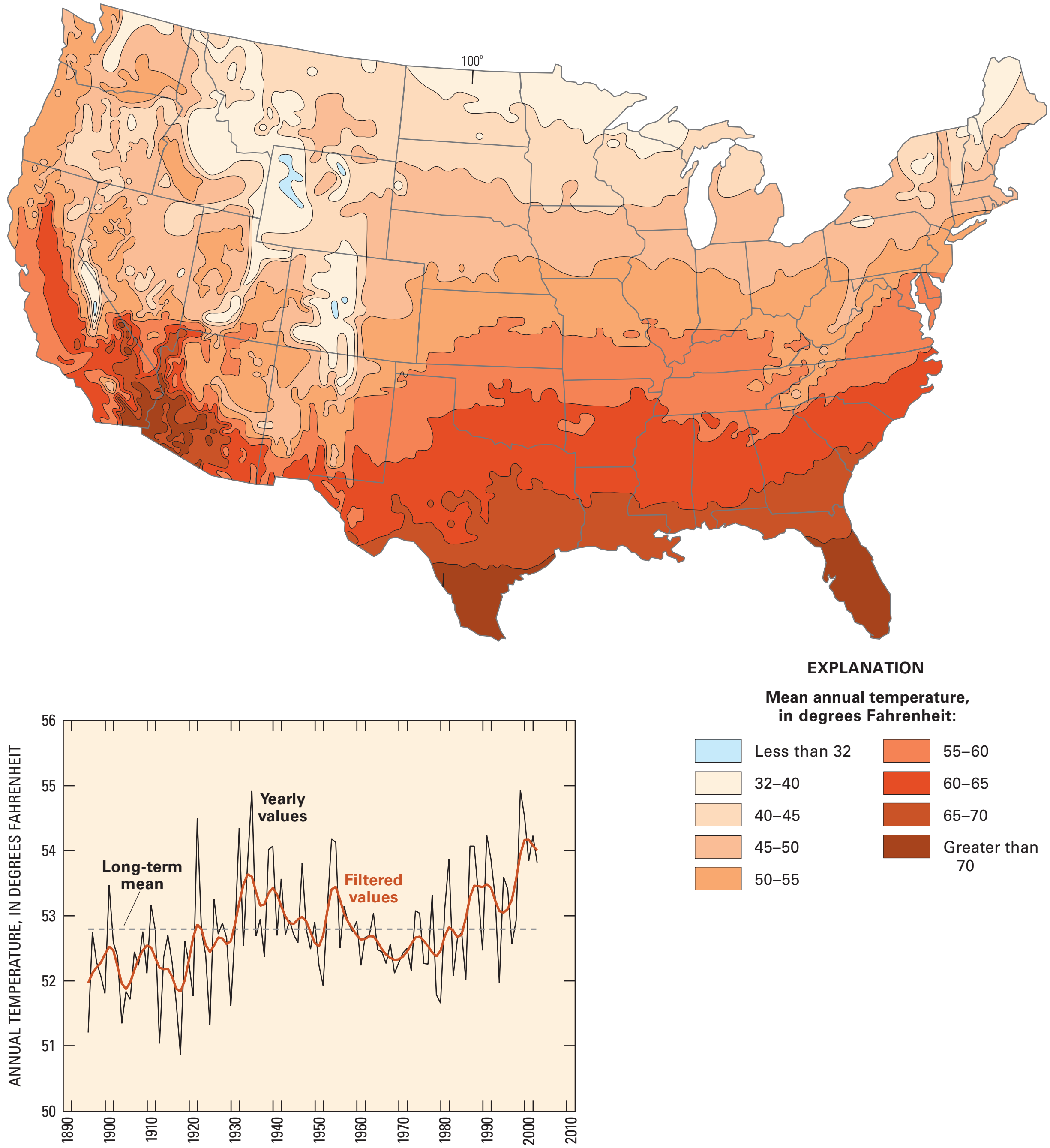


Figure 4. *Mean annual temperatures for the contiguous United States, 1890 to 2002. (Source: National Oceanic and Atmospheric Administration, National Climatic Data Center).*

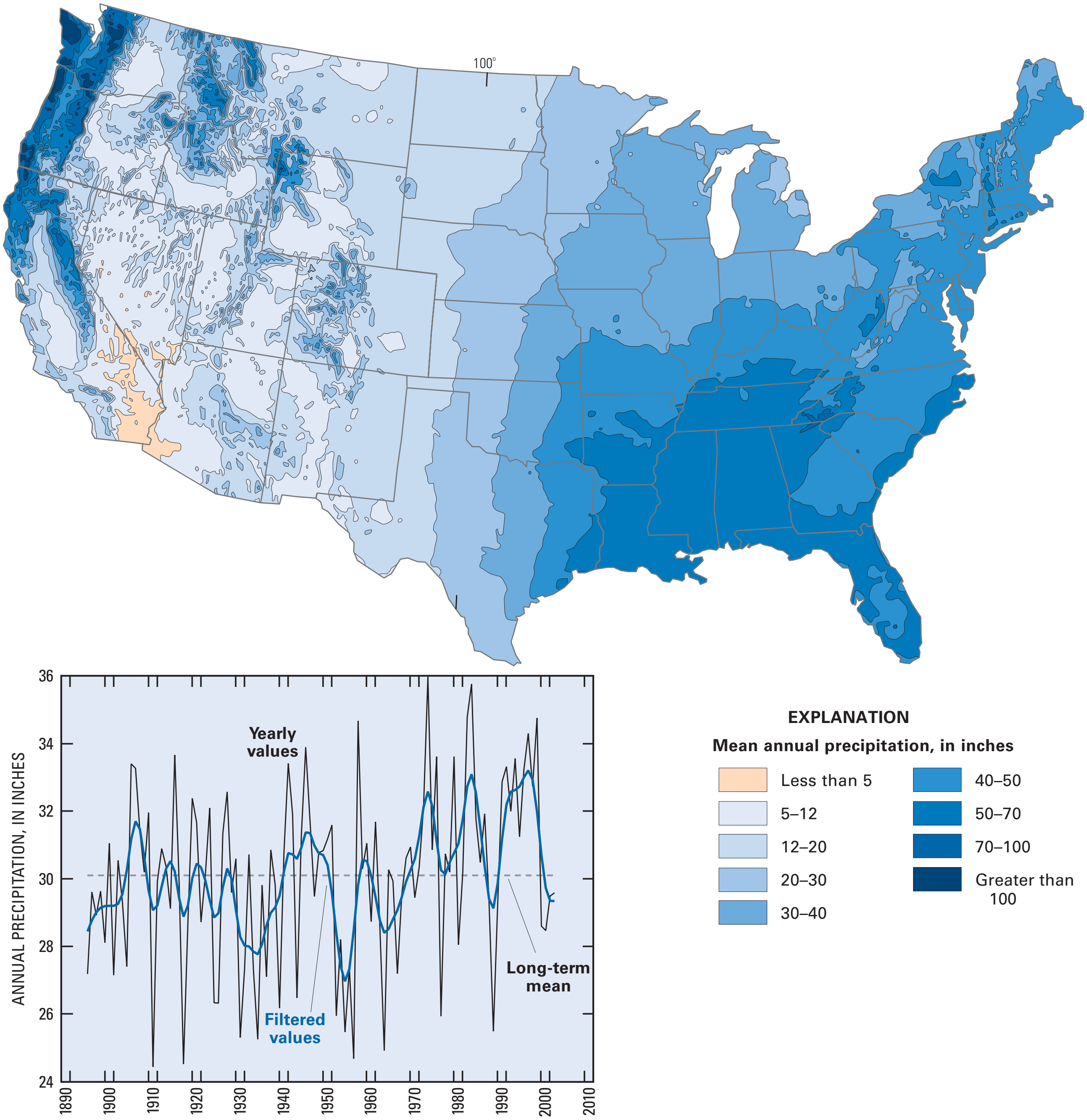


Figure 5. *Mean annual precipitation for the contiguous United States, 1890 to 2002. (Source: National Oceanic and Atmospheric Administration, National Climatic Data Center).*

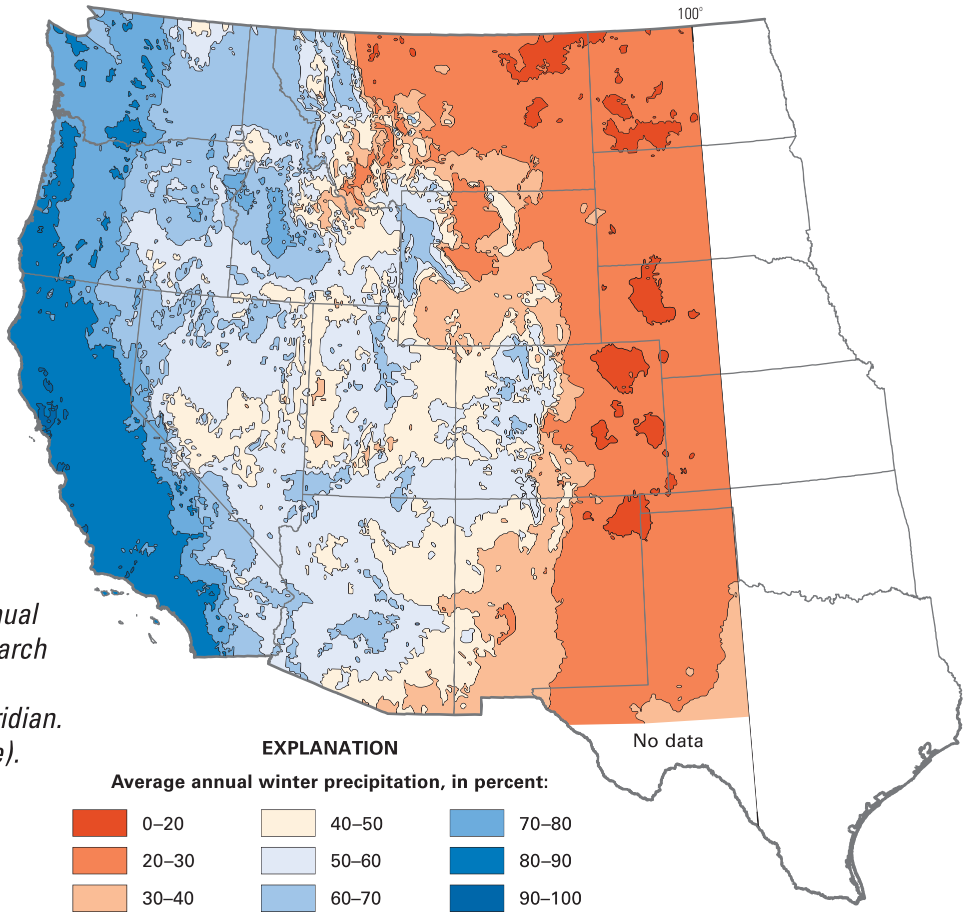


Figure 6. *Percentage of average annual precipitation that falls in October–March for the contiguous Western United States. Data extend to the 100th Meridian. (Source: Oregon State Climate Office).*

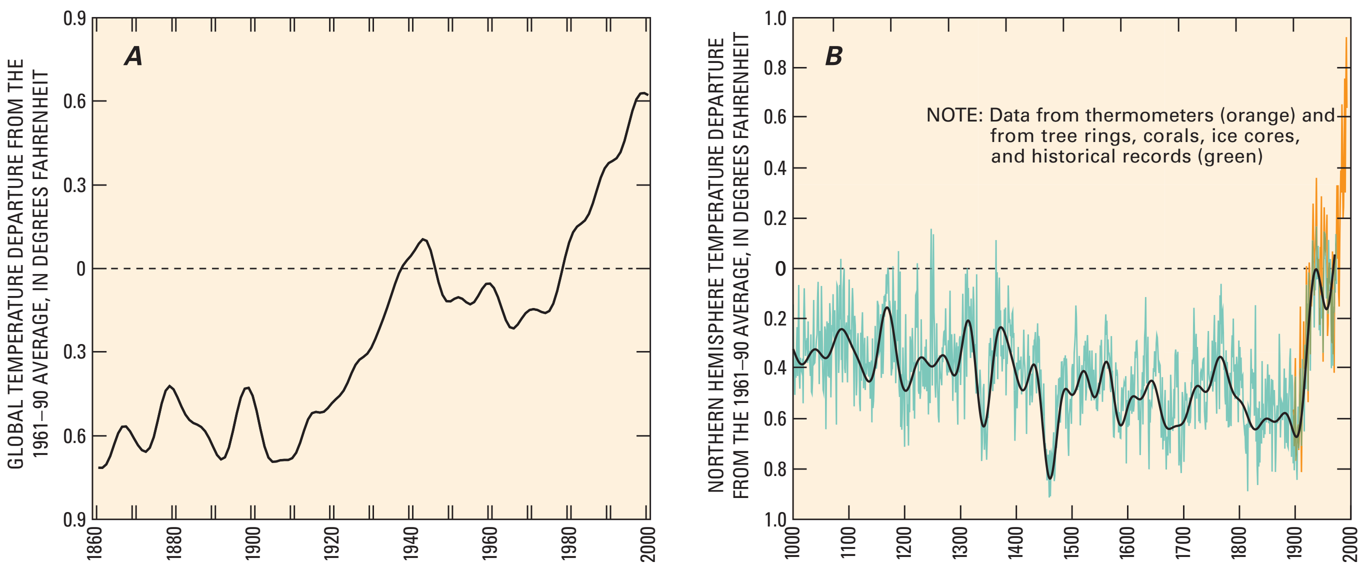


Figure 7. *Variations of Earth's surface temperatures for : A, the past 140 years. B, the last 1,000 years. From Intergovernmental Panel on Climate Change (2001a).*

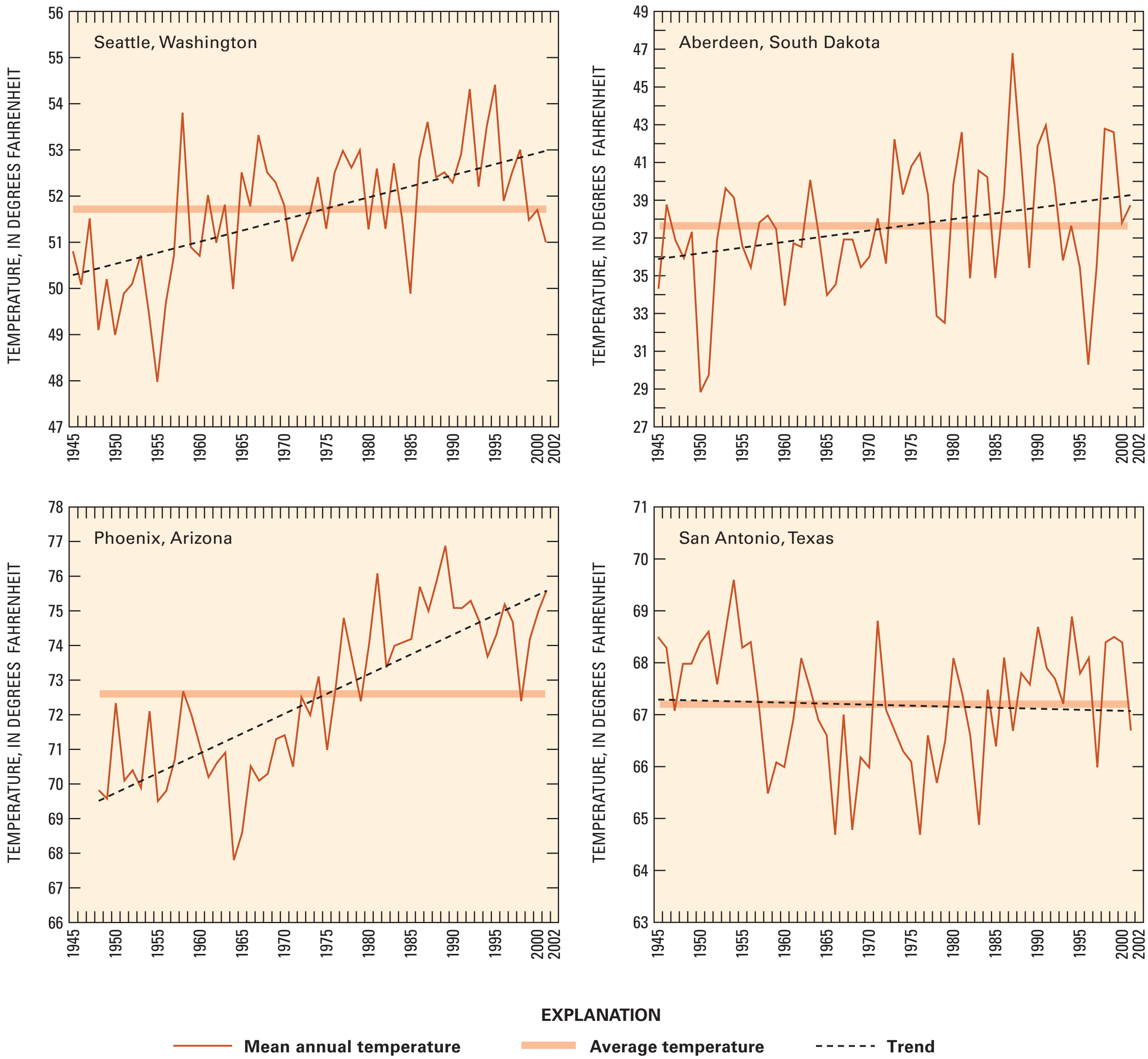


Figure 8. *Trends in mean annual temperature for selected cities in the Western United States. (Source: National Oceanic and Atmospheric Administration, National Climatic Data Center).*

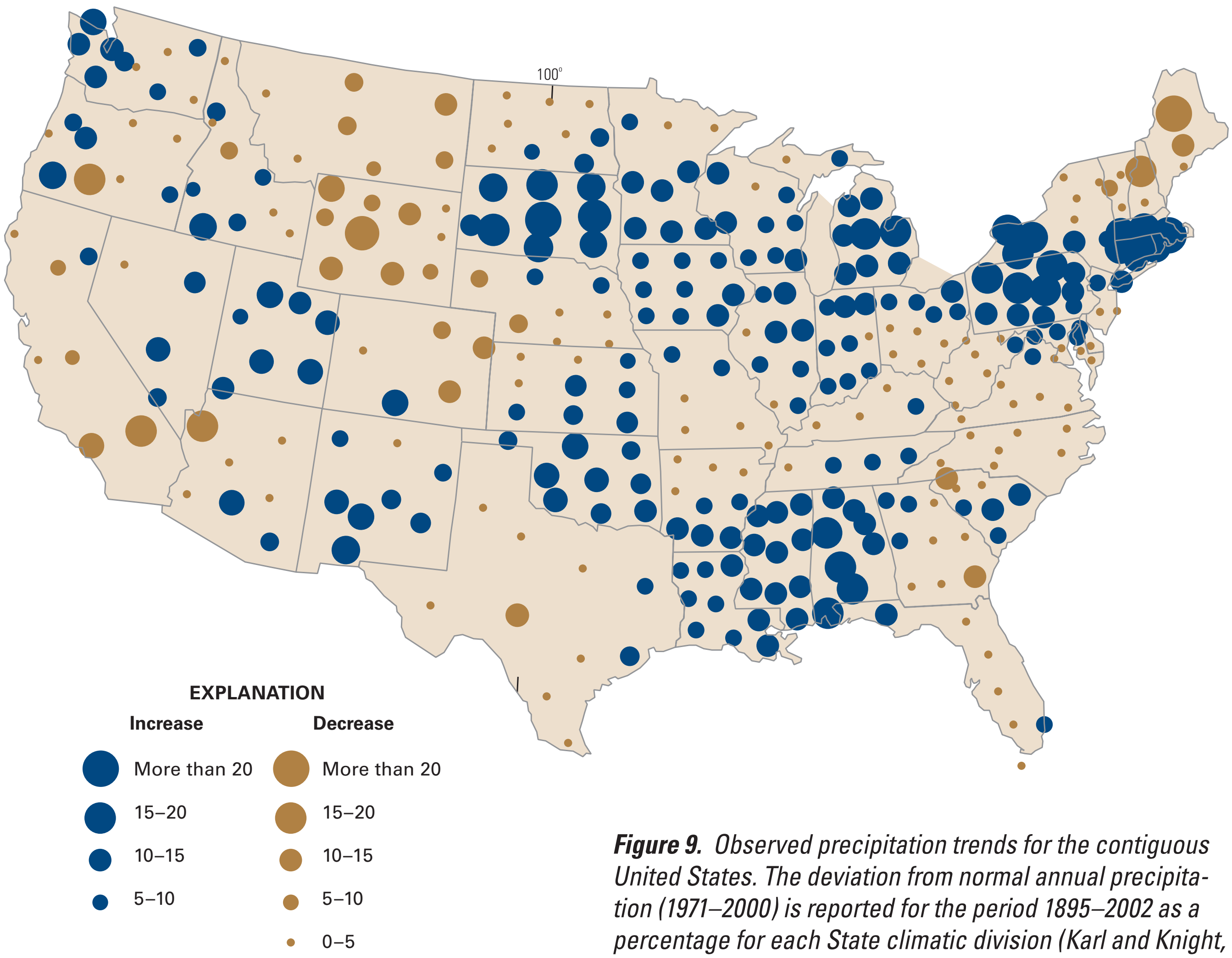


Figure 9. *Observed precipitation trends for the contiguous United States. The deviation from normal annual precipitation (1971–2000) is reported for the period 1895–2002 as a percentage for each State climatic division (Karl and Knight, 1998). The diameter of the circle centered within each climatic division reflects the deviation from normal. (Source: National Oceanic and Atmospheric Administration, National Climatic Data Center).*

Water Availability and Patterns

Freshwater on the continent is a limited but renewable resource. The renewable portion is of greatest interest because, in theory, simultaneously satisfying human and ecosystem needs will need to be achieved through proper management of this component. Rivers, streams, reservoirs, and lakes constitute the surface-water portion of the freshwater supply, and in most cases, flow and quantities of water in storage can be measured. Ground water is present in aquifers at varying depths, but only water near the land surface (less than 2,000 feet) realistically is available for use. Flow and storage volume of ground water are much more difficult to estimate than for surface water, but specific components, such as change in aquifer storage, can be measured. Except for the possibility that climate change may bring additional rainfall to some locations, it is this relatively constant amount of water that is available to support population growth and sustain ecosystems. The amount of renewable freshwater and the amount of freshwater in storage, therefore, is important to know, but seldom collectively inventoried.

Surface Water

In 2002, the flow of water in the streams and rivers of the United States was measured by a network of about 7,000 streamflow-gaging stations operated by the USGS. About 3,400 of these stations are in the 17 Western States (fig. 10). The total volume of water flowing from the continent is substantial, but unfavorably distributed, at least from the standpoint of human use. A large amount of the total runoff from the Western United States flows into the ocean from the rivers of the Pacific Northwest where population density is lower than in the Southwest.

There is a widespread perception that streamflow in the West is decreasing. Analysis of mean daily streamflow for selected major Western rivers for 1950 to 2000, however, indicates either no trend, or a significant increasing trend. These trends occur despite alterations in the flow regime due to reservoir operations. The annual mean daily streamflow for selected major rivers in the West is shown in figure 11. There is an increasing monotonic trend ($p \geq 0.05$) in annual streamflow, as determined by the Kendall's tau test (Conover, 1980), for the Rio Grande and Columbia Rivers (1950 to 2000). There is an apparent increase in streamflow in five of the seven rivers, presented in figure 11, for the final decade of 1990 to 2000, but the apparent trend is not statistically supported.

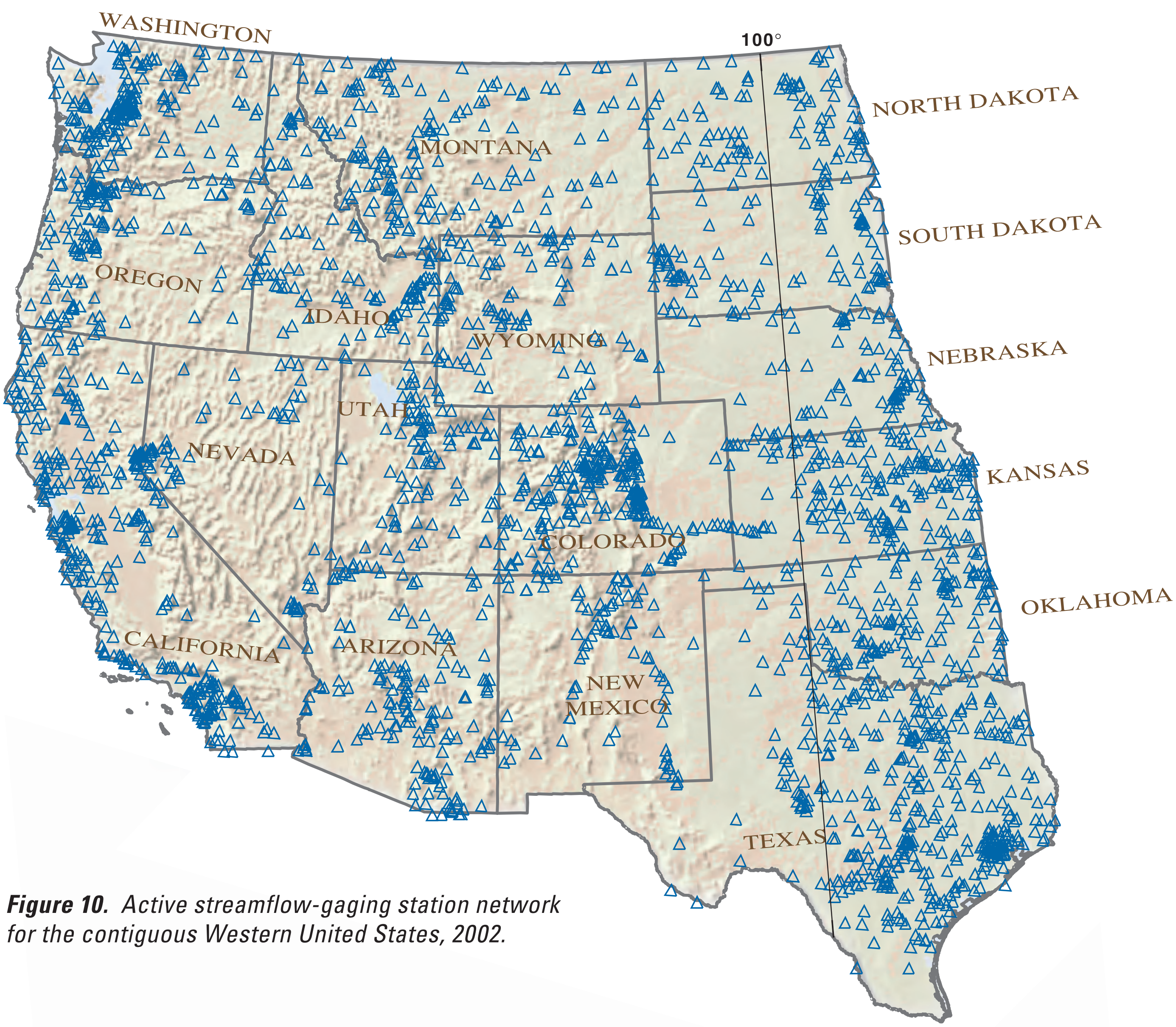


Figure 10. *Active streamflow-gaging station network for the contiguous Western United States, 2002.*

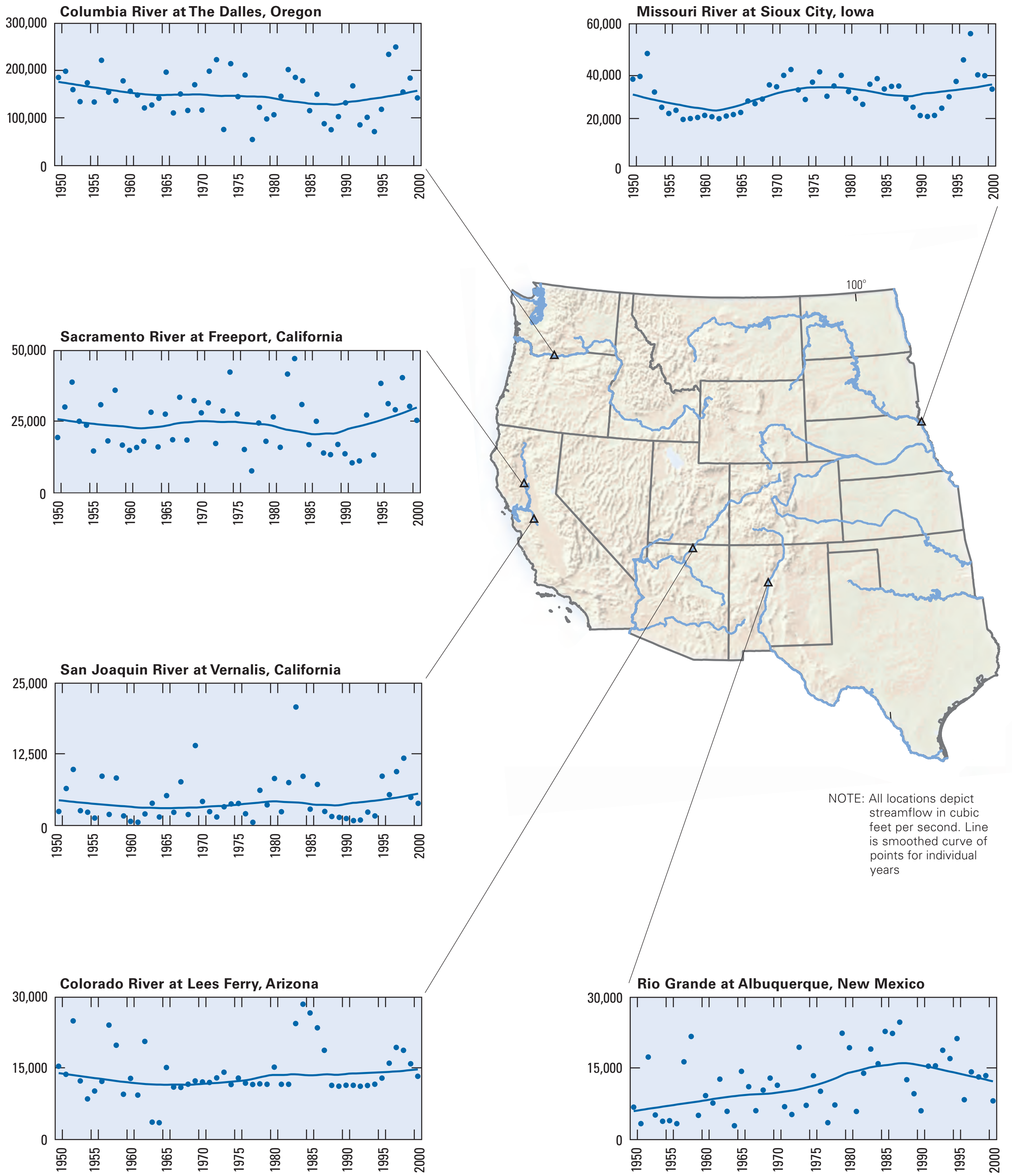


Figure 11. *Annual mean daily streamflow, in cubic feet per second, for selected major rivers in the contiguous Western United States.*

A distinguishing characteristic of the Western rivers is the large proportion of reservoir storage compared to annual flow (table 1). In the case of the Rio Grande, total reservoir storage is about 28 times the annual mean flow of the river. Lake Powell stores 24 million acre-feet at full pool, which is about three times the annual discharge of the Colorado River at Lees Ferry, Arizona. Annual flows in Western rivers between years, therefore, can reflect adjustments in reservoir storage, which is affected by precipitation in the contributing watershed and water demands downstream.

Total reservoir contents have declined in recent years for the Rio Grande and the Colorado and Missouri Rivers. Historical lows were set in 2003 for the Rio Grande and the Colorado Rivers at least since the reservoirs reached full operating potential (fig. 12). The current drought (1996–2004) in the Southwest has reduced inflows to most Western reservoirs, lowering water levels and depleting reservoir storage. The declining water levels in major reservoirs have substantially reduced opportunities for recreational activities, such as boating and swimming.

The streamflow record for the United States has been examined by several investigators for evidence of significant trends over time (Lins and Slack, 1999; Dettinger and Diaz, 2000). Of particular interest is whether the increasing trend of precipitation (attributed in part to global warming) is manifesting itself as a corresponding increase in streamflow. Lins and Slack (in press) reported trends of increasing annual minimum and median streamflows for most of the 435 streamflow-gaging stations examined that together monitor broad sections of the United States (fig. 13). Decreases were found only in parts of the Pacific Northwest and the Southeast United States. McCabe and Wolock (2002) report a similar increase in annual minimum and median flows, but in the form of a step, rather than a gradual trend, that occurred around 1970. The pattern of increasing streamflow reported by Lins and Slack (1999) was most pronounced in the central two-thirds of the United States and to a lesser extent in the Great Basin. Relatively few trends are observed in the annual maximum flow. No systematic shift in the timing of the annual minimum, median, or maximum flow is detected in any region, although the temporal resolution was at the monthly scale, and shifts of several weeks could not be precluded. The observed increases in low to moderate streamflows, typical of the warm and transitional seasons, are consistent with documented trends in warm and transition-season precipitation. Lins and Slack (1999) conclude that the natural supply of surface water in the United States has increased and has done so without a concomitant excess water penalty (flooding). In an apparent contradiction, Groisman and others (2001) report a significant increase in peak discharges for the contiguous United States. Milly and others (2002) report an increased risk of great floods—those having a return frequency greater than 100 years—that can be attributed to climate forcing, but most of the basins where such increases were determined were in the high northern latitudes of Russia and Canada. According to Milly and others, these findings are tentative and will need to be confirmed by the analysis of longer streamflow records. Continued monitoring and research can be used to resolve these apparently disparate results of streamflow-record analyses.

Table 1. *Comparison of the mean annual discharge volume of selected major rivers in the West to total reservoir capacity in those watersheds.*

River system (fig. 12)	Mean annual discharge (millions of acre-feet per year)	Period of record	Total reservoir capacity (millions of acre-feet)
Colorado	11	1922–2000	61
Columbia	139	1879–2000	100
Missouri	22	1929–2000	[1]73
Rio Grande	0.7	1917–2000	[2]20
Sacramento	17	1949–2000	16
San Joaquin	3.4	1930–2000	10

[1]Main-stem reservoirs only.

[2]Reservoir capacity for all reservoirs in the U.S. and Mexico, including two international reservoirs.

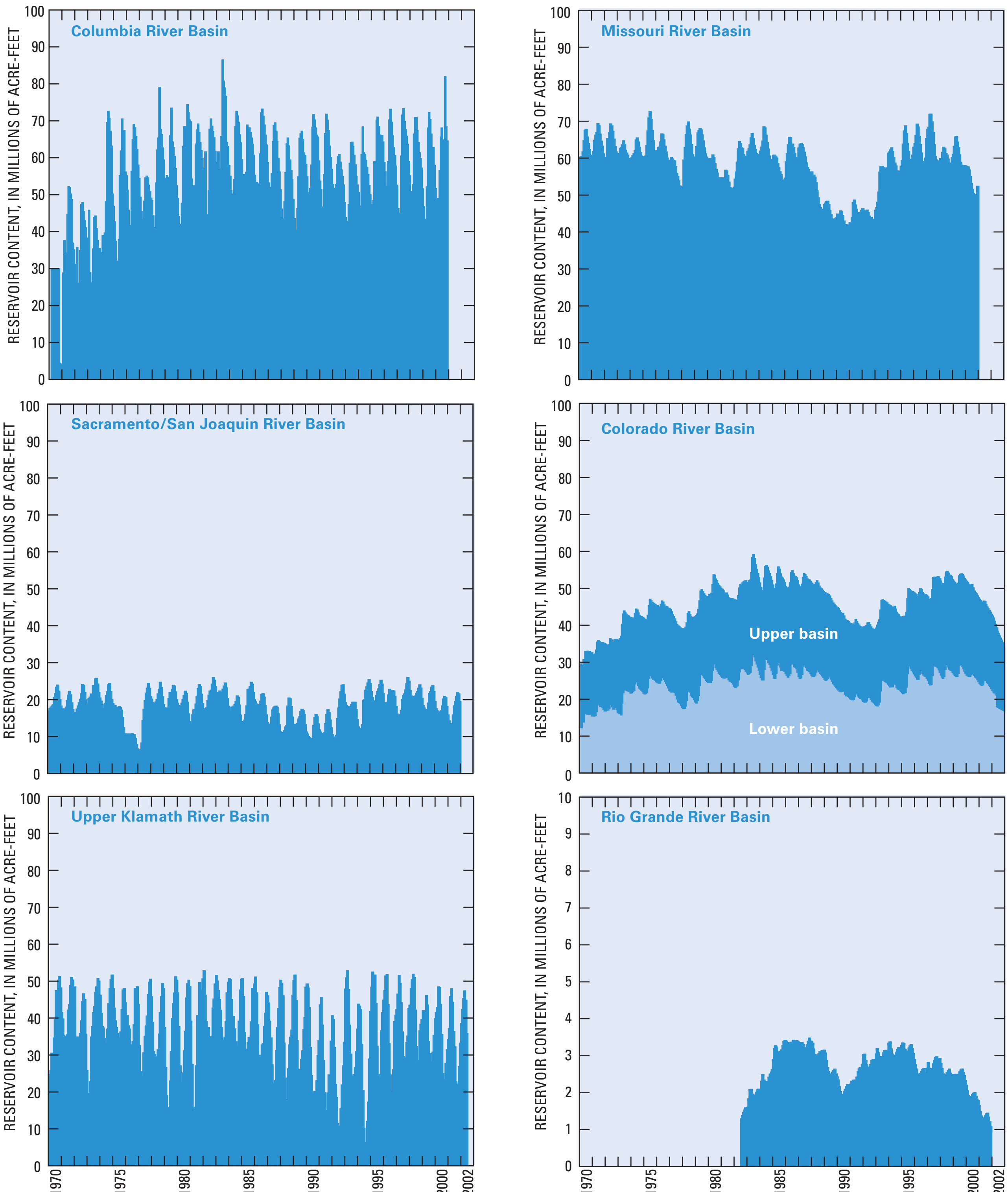


Figure 12. *Trends in reservoir contents for selected major managed rivers in the contiguous Western United States. (Source: Bureau of Reclamation (unpublished data), U.S. Army Corps of Engineers (unpublished data).*

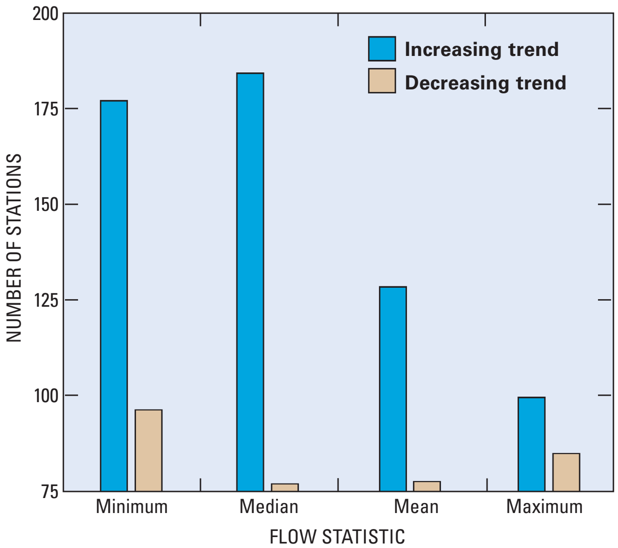


Figure 13. *Number of streamflow-gaging stations in the United States, out of a total of 435, having statistically significant (p equal to or less than 0.05) trends for 1940–99. Modified from Lins and Slack (in press).*

The timing of streamflow is important to reservoir storage, flood mitigation, and the management of water supplies. If winter and spring air temperatures are warmer, streamflow from snowmelt-dominated basins will occur earlier in the year, because snowpacks melt more quickly and more precipitation falls as rain rather than snow. Such changes in streamflow timing can be characterized using several approaches. Dettinger and Cayan (1995) analyzed the annual fractions of streamflow that occur in spring and summer seasons. Cayan and others (2001) examined "spring pulse dates" when wintertime low-flow conditions abruptly change to springtime high-flow conditions with the onset of warm-season snowmelt. Stewart and others (2004) used a "center of mass" of each year's streamflow hydrograph to examine streamflow timing. By all these measures, the seasonality of runoff is changing in snowmelt-dominated basins of the West (fig. 13). Flows in many Western rivers now arrive 1 to 3 weeks earlier than in the mid-1900s (Stewart and others, 2004). The greatest changes are evident in the Pacific Northwest, but trends also are present in the Sierra Nevada of California, in the Rocky Mountains, and in southern Alaska.

A declining trend in the fraction of streamflow arriving in the spring has been reported for northern California rivers (Roos, 1991; Dettinger and Cayan, 1995; Gleick and Chalecki, 1999). Knowles and Cayan (2002) point out the vulnerability of California's regional hydrologic system to projected global climate change. A projected temperature increase of 2.1º Celsius by 2090 will result in a further loss of April snowpack storage, with greatest losses in the northern headwaters. Several studies summarized in "Climate Change 2001: Impacts, Adaptation and Vulnerability" (Intergovernmental Panel on Climate Change, 2001a) show similar seasonal shifts to increased winter runoff and reduced summer flows. Changes in snowfall and snowmelt dynamics for the West, even if annual amounts of precipitation changed little, would be an important consequence of a warmer climate, especially given the importance of high-elevation precipitation to the available water supply. The consequences of these changes in streamflow timing trends may include (1) a reduction in the amount of runoff that occurs in the high-demand spring and summer seasons; (2) an increase in the amount of runoff during the winter-storm season, thereby decreasing the available flood storage space; and (3) reducing the water available to sustain soil and fuel moisture throughout the summer, which could initiate ecosystem changes (Dettinger and others, 2004).

Ground Water

Ground water is an important resource, especially in the West. The total volume of ground water in storage is much larger than the volume of surface water in all the lakes, streams, and rivers of the United States at any given time. Many communities in the West depend upon ground water as an important component of their water supply; in some cases, ground water is their exclusive supply. In the United States, ground water is the source of drinking water for 50 percent of the population and as much as 90 percent of the population in rural areas, especially in the West (fig. 14; U.S. Geological Survey, 1998). Despite the importance of ground water to the Nation, there is no national program to systematically monitor ground-water conditions in the United States (Taylor and Alley, 2001). Reporting on trends of ground-water availability, therefore, is less quantitative than that for surface water. Some individual aquifers are being systematically monitored by the USGS or by other government agencies. Water levels are declining in aquifers that supply major population centers or major irrigated areas (fig. 15). The volume of water flowing through or stored in aquifers is more difficult to estimate with any degree of certainty compared to the volume of water in streams and rivers.

Each ground-water system is unique in that the source and volume of water flowing through the system is dependent upon external factors, such as the rates of precipitation, recharge, evaporation, and evapotranspiration; and the location and hydrologic connection with streams, rivers, springs, reservoirs, and wetlands. The one common factor for all ground-water systems, however, is that the total volume of water entering, leaving,

Figure 14. *Percentage of population of each State in the contiguous Western United States dependent on ground water for domestic water needs. From U.S. Geological Survey (1998).*

and being stored in the system must be conserved. An accounting of all the inflows, outflows, and changes in storage is called a water budget (fig. 16). Basin-wide water budgets are needed to properly manage ground-water resources.

Under predevelopment conditions, a ground-water system is in long-term equilibrium (fig. 16*A*). That is, averaged over some period of time, the volume of water entering or recharging the system is approximately equal to the volume of water leaving or discharging from the system. Because the system is in equilibrium, the quantity of water stored in the system is constant or varies about some average condition in response to annual or longer term climatic variations.

An equation that describes the water budget of the predevelopment ground-water system is:

Recharge (water entering) = Discharge (water leaving).

The ground water leaving a basin or being discharged to streams and rivers is called base flow.

Humans change the natural or predevelopment ground-water flow system by withdrawing (pumping) water for use (fig. 16*B*), increasing recharge by application of water to the land surface or by direct injection, and decreasing recharge by paving over permeable soils. In all cases, the source of water for pumpage will be supplied by (1) more water entering the ground-water system (increased recharge), (2) removal of water that was stored in the system, (3) less water leaving the system (decreased discharge), or (4) some combination of the first three conditions.

It is important that ground-water monitoring programs be based on an understanding of the water budget to put in context the rate of usage compared to the renewable supply of water. Actual measurements of the budget components are preferred whenever possible, but if they

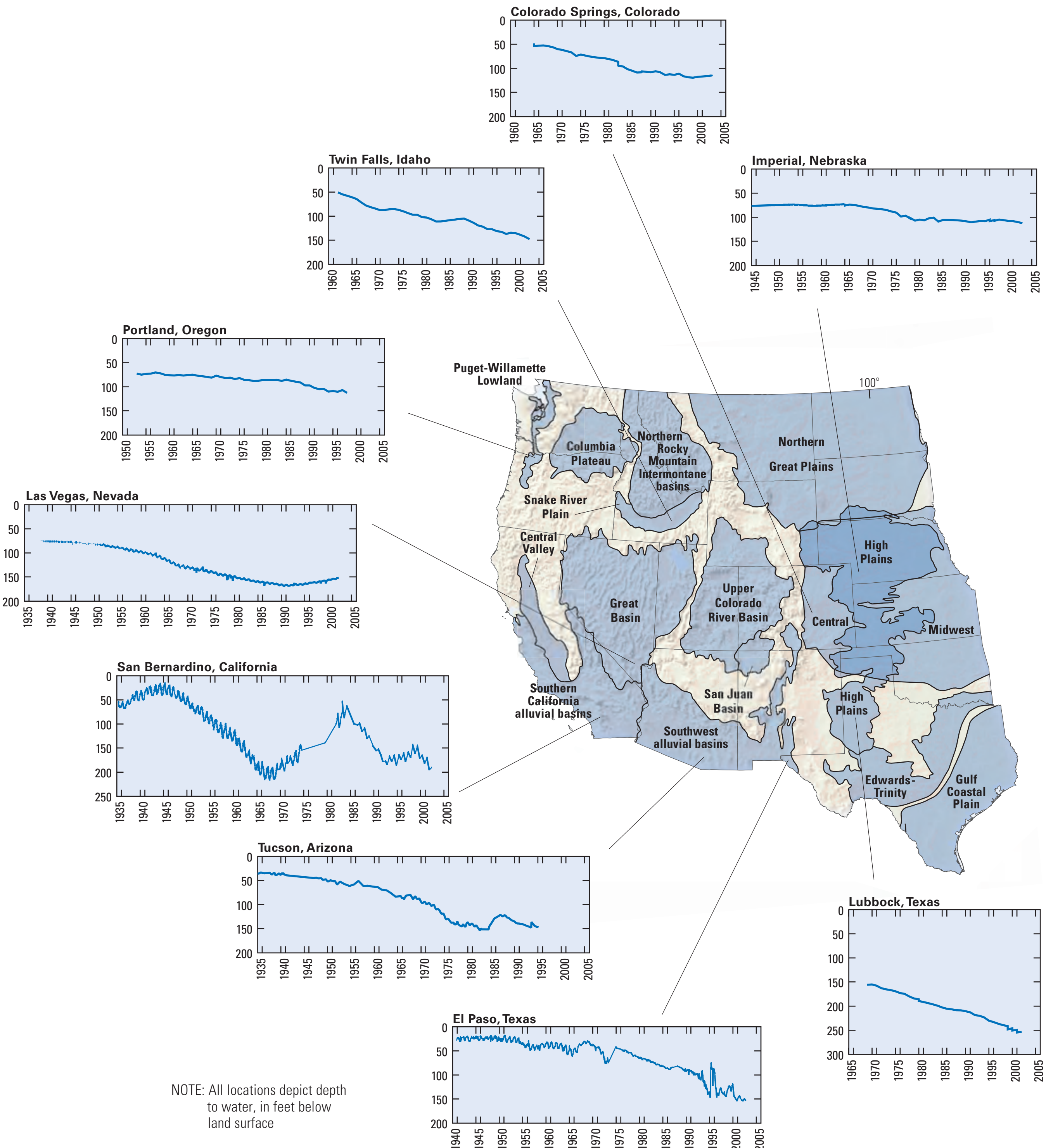


Figure 15. *Major aquifers in the contiguous Western United States and select hydrographs showing changes in depth to water below land surface.*

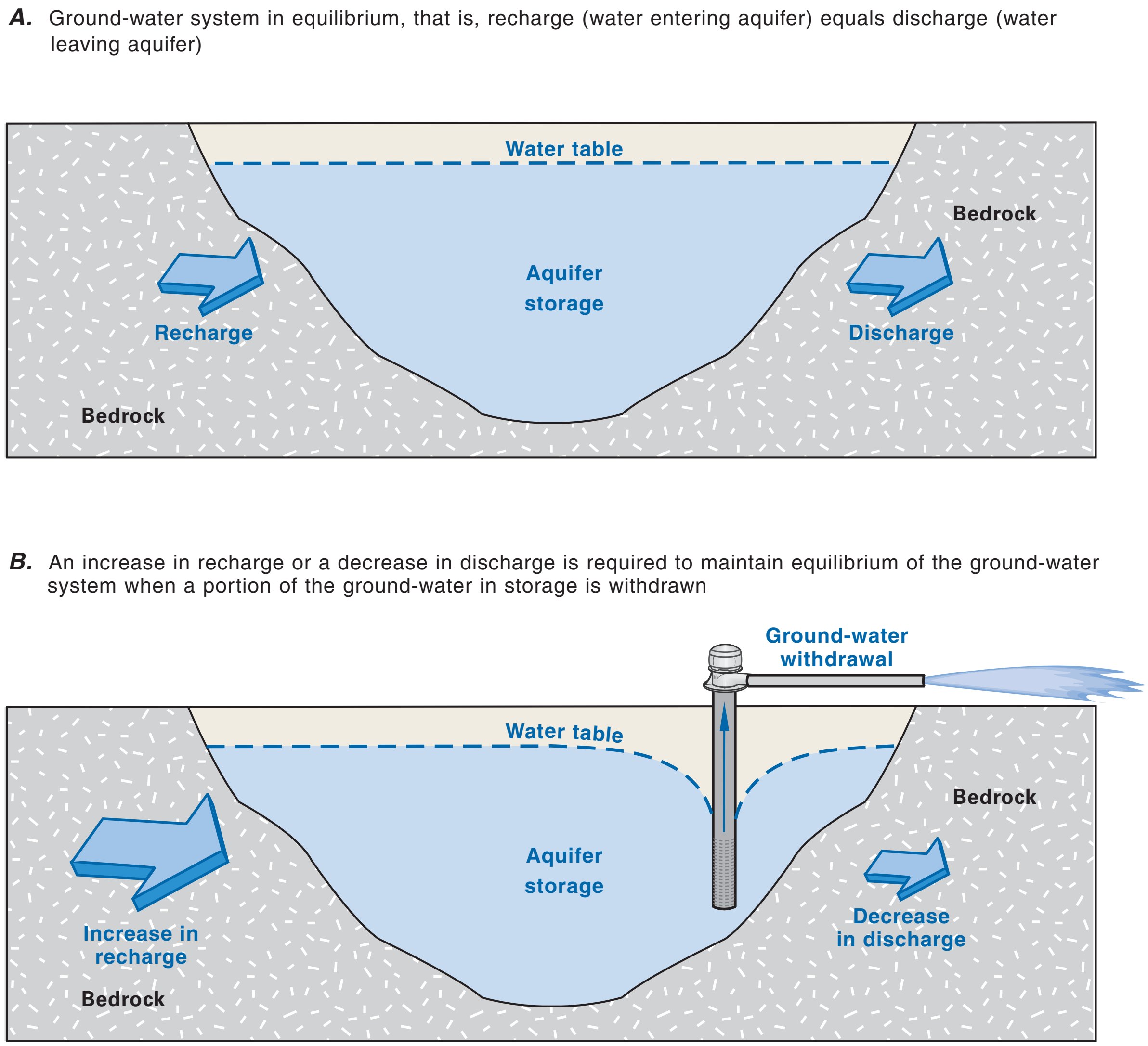


Figure 16. *Simplified ground-water budget for: A, Ground-water system in equilibrium. B, Ground-water system with pumping.*

are not available, estimates are used. The relative difference (or balance) between inflows and outflows can be revealed by monitoring changes in storage. If storage is declining consistently over time, outflows, a portion of which is pumpage, must exceed inflows. The aquifer-storage term, therefore, is an important and useful budget component to monitor; however, all components of the budget should be improved where practical. Aquifer-storage change and water use (pumpage) estimates can be improved substantially with today's technology. Better information on all budget components, however, will improve the basis upon which water-resource decisions are made. When aquifer storage is consistently depleted, other adverse consequences can result, such as land-surface subsidence, increases in stream capture that result in reduced streamflow, drainage of wetlands, or cessation of spring flow.

Aquifer-storage change, despite its usefulness as an indicator of resource condition, is not being systematically monitored for all the Nation's principal aquifers—a limitation that significantly hampers the assessment of trends in ground-water availability. Two methods are available to determine aquifer-storage change: (1) comparing water levels between time intervals, and (2) measuring directly the mass change using gravity methods.

Most States or local water agencies support some program of water-level monitoring. A water level in a single well can be interpreted only to a limited extent, but is useful as an indicator of local changes in storage. The systematic collection of water-level data over time from a network of wells distributed throughout an aquifer provides much more useful information. With these data, the change in storage within an unconfined (water table) aquifer system can be computed by determining the change in volume between time intervals, and when multiplied by specific yield, the product approximates storage change (fig. 17). Specific yield is a dimensionless term that represents the volume of water that can be drained from an aquifer under the influence of gravity (Heath, 1987). Simplifying assumptions are necessary, such as selecting an average value to represent specific yield across and at depth within a regional unconfined aquifer.

An aquifer-wide monitoring program is currently in place for the High Plains aquifer (fig. 15). Systematic water-level measurements began in the 1980s, and the USGS periodically publishes maps of water-level change (McGuire, 2001; McGuire and others, 2003). Aquifer storage has been computed from these water-level-change data (Barlow and others, 2002). (See Box A—High Plains Aquifer.)

Aquifer-storage change also can be determined by measuring the subtle changes in the pull of gravity detected by a sensitive meter known as a gravimeter. Ground water is stored within the pore spaces of aquifers. As an aquifer is drained by pumpage or filled by recharge, its mass changes, which results in changes in the strength of its gravitational field. Recent technological advances in geophysical techniques have made it practical to measure the extremely small gravitational changes caused by fluctuations of water volume. The use of microgravity measurements to determine aquifer-storage change is a substantial technological advance over water-level-change computations. More sites can be measured in a given time period, and no broad estimate of specific yield is required. The accuracy of the storage-change estimate is improved as a result.

The USGS monitors a network of gravity stations throughout the Tucson Basin and Avra Valley in southern Arizona (see Box B—Microgravity). This project is the first basinwide application of microgravity methods to measure changes in ground-water storage. Storage change from the winter of 1999 through the winter of 2002 is shown for the Tucson Basin in figure 18.

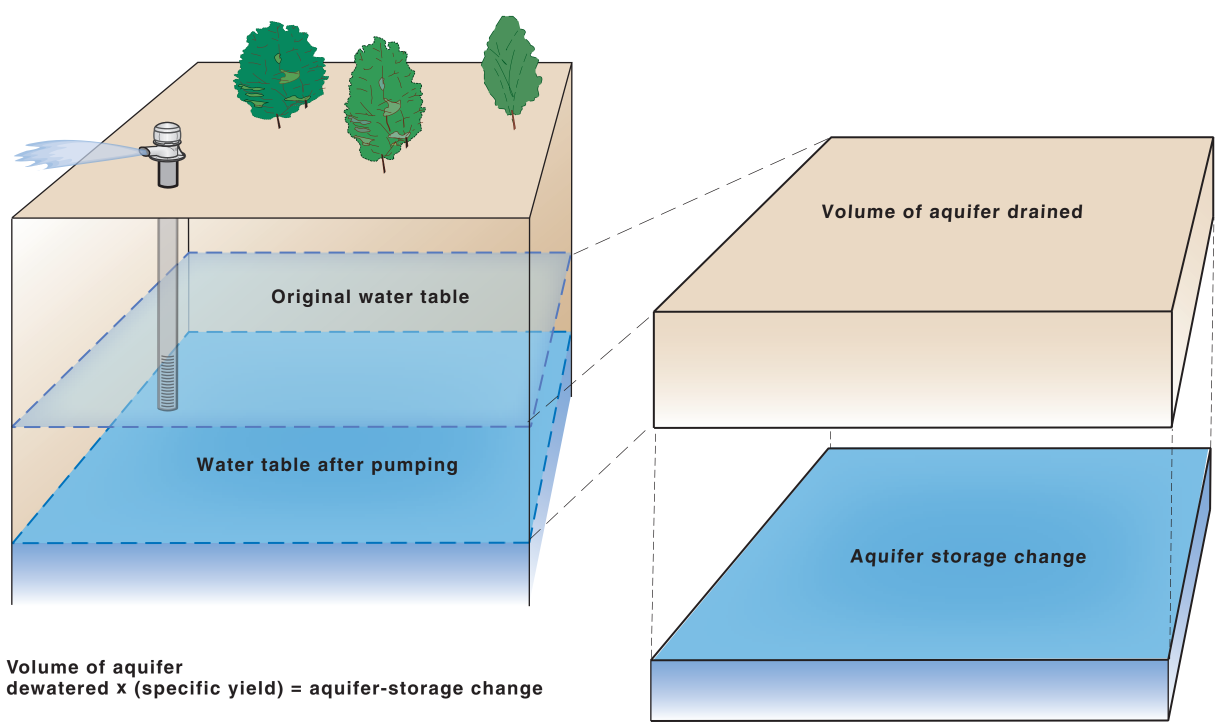


Figure 17. *Determination of aquifer-storage change for an unconfined aquifer from water-level measurements and an estimate of specific yield (Sy = 1). Specific yield is a ratio of the volume of water that drains from a volume of aquifer by gravity. For example, if the volume is filled with water (as in a lake), the specific yield equals 1 (Sy = 1). Because the aquifer materials occupy some of the volume in the aquifer, a typical specific yield value for an aquifer is 0.2 or 20 percent (Sy = 0.2).*

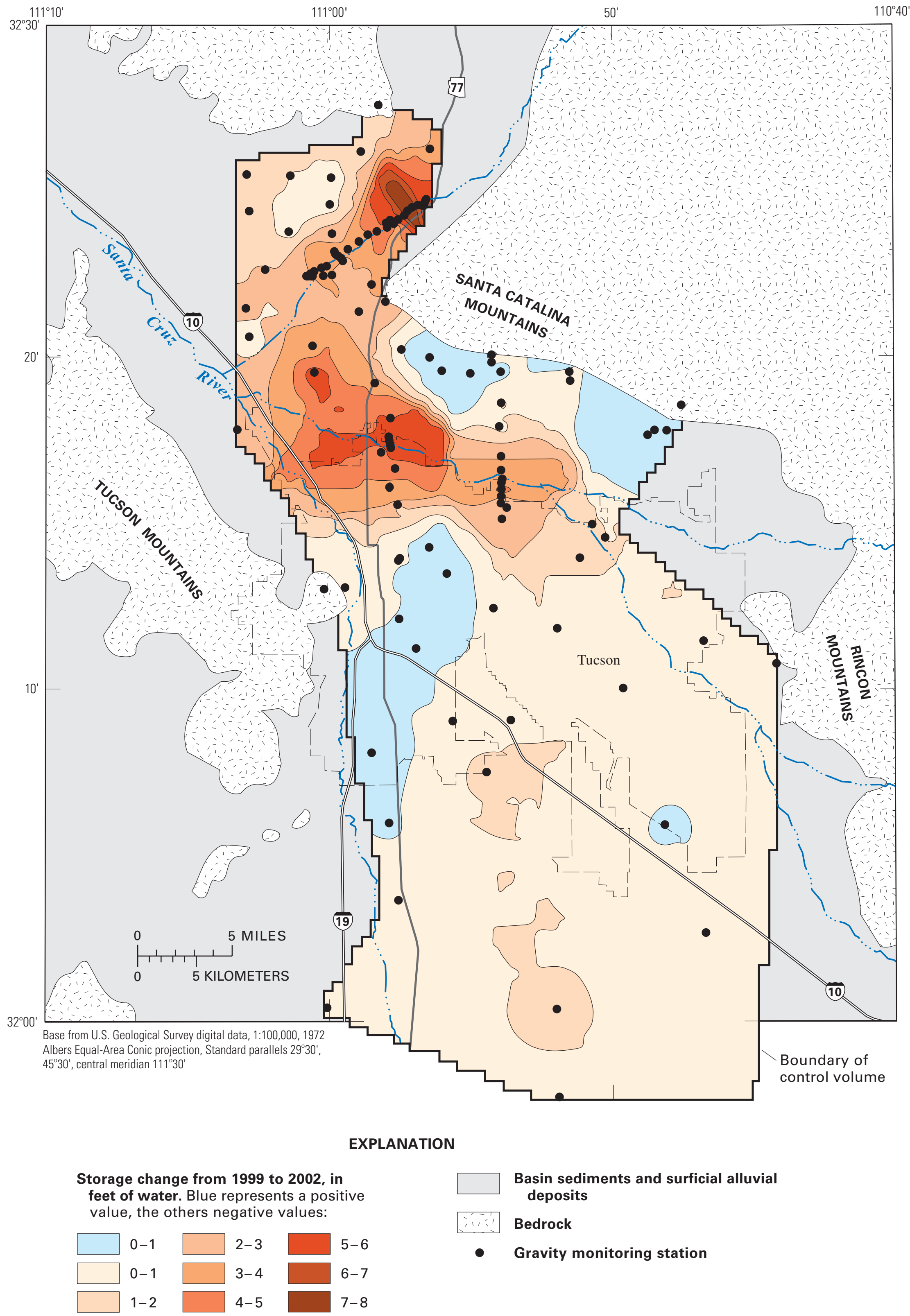


Figure 18. *Example of ground-water storage change in the Tucson Basin, Arizona, determined by microgravity measurements. (Source: Don Pool, U.S. Geological Survey, written commun., 2003.)*

Water-Level Monitoring and Ground-Water Storage Change in the High Plains Aquifer

Water-level monitoring of the High Plains aquifer has documented water-level declines and recoveries since the 1980s and is a good example of the need for systematic monitoring to assess ground-water availability and aquifer conditions. The High Plains aquifer extends over a 174,000-square-mile area, underlying parts of eight States from South Dakota to Texas. Water is pumped from the aquifer for municipal use and irrigation, which has made the High Plains one of the Nation's most important agricultural areas.

The intensive 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 near levels at which it will no longer be economical to use the aquifer for large-scale irrigation. The changes are particularly evident in the central and southern High Plains (see fig. 1*A*), where in some areas more than 50 percent of the redevelopment saturated thickness has been dewatered (Barlow and others, 2002).

In response to declines in the water level and ground-water storage, a monitoring program was begun across the High Plains in 1988 to assess annual water-level change in the aquifer. Water-level measurements have been made each year in more than 7,000 wells. The water-level data also are used to determine storage changes (fig. 1*B*), which are a valuable indicator of aquifer condition. This substantial effort requires collaboration among numerous Federal, State, and local water-resource agencies.

It can be misleading to make generalized statements about the aquifer as a whole, but in many areas, water levels continue to decline. The monitoring program indicates overall reductions in the rate of decline during the past two decades in some areas. This change is attributed to decrease in irrigated acreage, reduced water needs because of improved irrigation and cultivation practices, and above-normal precipitation and recharge during this period (McGuire and Sharpe, 1997).

Water-level declines increase pumping lift, decrease well yields, and limit development of the ground-water resource. The estimated net amount of water removed from storage in the aquifer is 200 million acre-feet from redevelopment through 2001, which is a large volume of freshwater—equal to more than half the volume of water in Lake Erie.

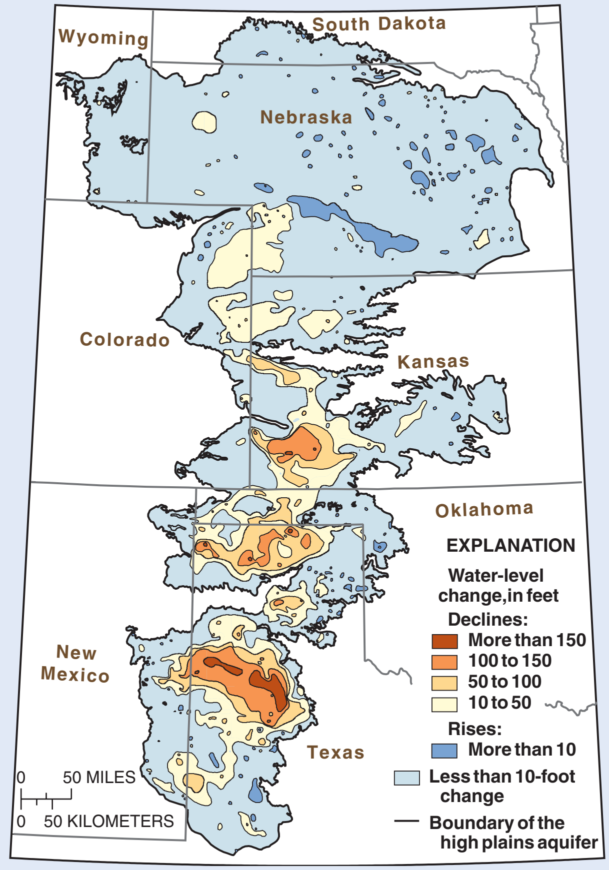


***Figure 1A.** Changes in ground-water levels in the High Plains aquifer from predevelopment to 2001 (V.L. McGuire, 2003).*

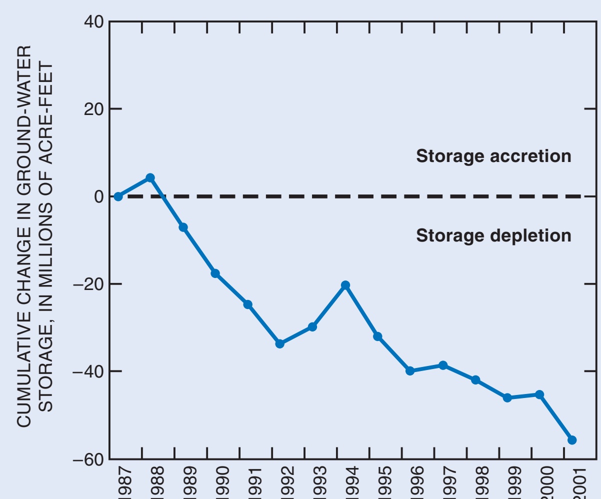
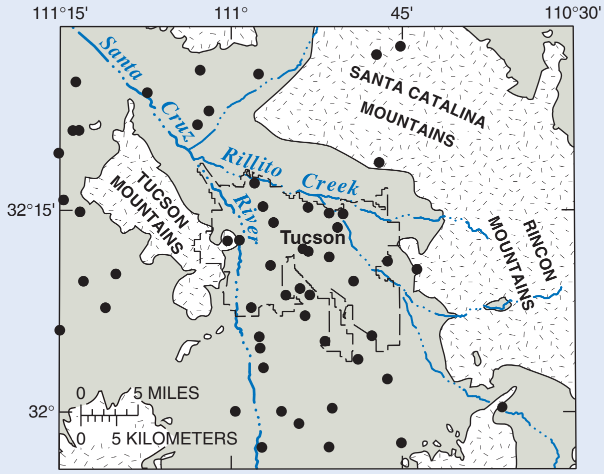


***Figure 1B.** Cumulative changes in ground-water storage in the High Plains aquifer since 1987. Modified from Barlow and others, 2002.*

Use of Microgravity to Measure Ground-Water Storage Change in the Tucson Basin, Southern Arizona

It is critically important to monitor the availability of ground water in areas where ground water is the main source of supply, such as the Tucson Basin in southern Arizona. Typically, monitoring aquifer conditions involves measuring water levels in wells; however, this technique only partially describes ground-water conditions in a basin. A new application of geophysical technology is enabling USGS scientists to measure changes in the amount of water in an aquifer using a network of microgravity stations (Pool and Eychaner, 1995; Pool and Schmidt, 1997). This technique enables a direct measurement of mass change from which ground-water depletion and recharge can be estimated. Water levels in some wells in the Tucson area have declined more than 200 feet in the past 50 years. The Tucson Basin and Avra Valley are two ground-water basins that form the Tucson Active Management Area (TAMA), which by State statute must attain “safe yield” by the year 2025.

Microgravity methods are based on the principles of Newton’s Law of Gravitation that states the acceleration due to gravity within an object’s gravitational field is directly related to the mass of the object and inversely related to the distance to the center of the object. In simple terms, the greater an object’s mass, the stronger its gravitational field. Differences in measured gravitational fields over Earth’s surface have been used by geophysicists for years to map variations in crustal thickness, the presence of magma bodies, and the subsurface distributions of different rock types. Now, they are being applied to water.



Network of existing microgravity (aquifer-storage monitoring) stations in the Tucson Basin area. Modified from Parker and Pool, 1998.

Gravity meter setup at a microgravity station. Photograph provided by Mark T. Anderson, U.S. Geological Survey.

As an aquifer is drained by pumpage or filled by recharge, its mass changes, which results in changes in the strength of its gravitational field. Recent technological advances in geophysical techniques have made measurement of the extremely small gravitational changes caused by fluctuations of water volume practical. The standard unit of measurement for conventional gravity studies is the milligal, a unit equal to 10^{-3} cm/sec^2; microgravity work uses microgals, or 10^{-6} cm/sec^2. The USGS microgravity network is based on the University of Arizona network and is the first basinwide application of microgravity methods to the measurement of changes in ground-water storage.

Microgravity studies in the TAMA began in 1992 as part of a cooperative study by the USGS and the Pima County (Arizona) Department of Transportation and Flood Control District. Today (2004) the cooperators include: Tucson Water, Arizona Department of Water Resources, Metropolitan Water District, town of Oro Valley, and the town of Marana. The USGS-established network now includes about 200 microgravity stations within the TAMA to measure basinwide changes in ground-water storage.

The results of the first four intervals of microgravity monitoring show that storage change and recharge can vary considerably from year to year (table 2). Storage change ranged from a 66,000-acre-foot accretion in 1998–99, an El Niño year, to a 268,000-acre-foot depletion in 2000–2001—hence, the importance of systematically monitoring storage change, when one year may account for most of the recharge that occurs over many years. Some years, such as 1998–99, could account for most of the recharge to Western aquifers over a much longer time interval. Determining storage change using microgravity methods is applicable to most regional aquifers and could be used to assess ground-water conditions systematically throughout the Nation.

Aquifer-storage change also may be measurable from space. Aquifer storage also can be reduced by land subsidence, which can be detected from space. Interferometric Synthetic Aperture Radar (InSAR) uses satellite data and analysis to map changes in the land-surface elevation between time intervals. The National Aeronautics and Space Administration launched two space-based gravity-observation platforms in 2002. An experimental project, called the Gravity Recovery and Climate Experiment (GRACE), will test the feasibility of using space-based gravity measurements in concert with land-based measurements, for validation purposes, to monitor aquifer-storage change over regional aquifers such as the High Plains. This remote-sensing technology is expected to have utility at regional (77,220 square miles) scales. If successful, aquifer-storage change can be monitored on a regular basis, presumably at reasonable cost.

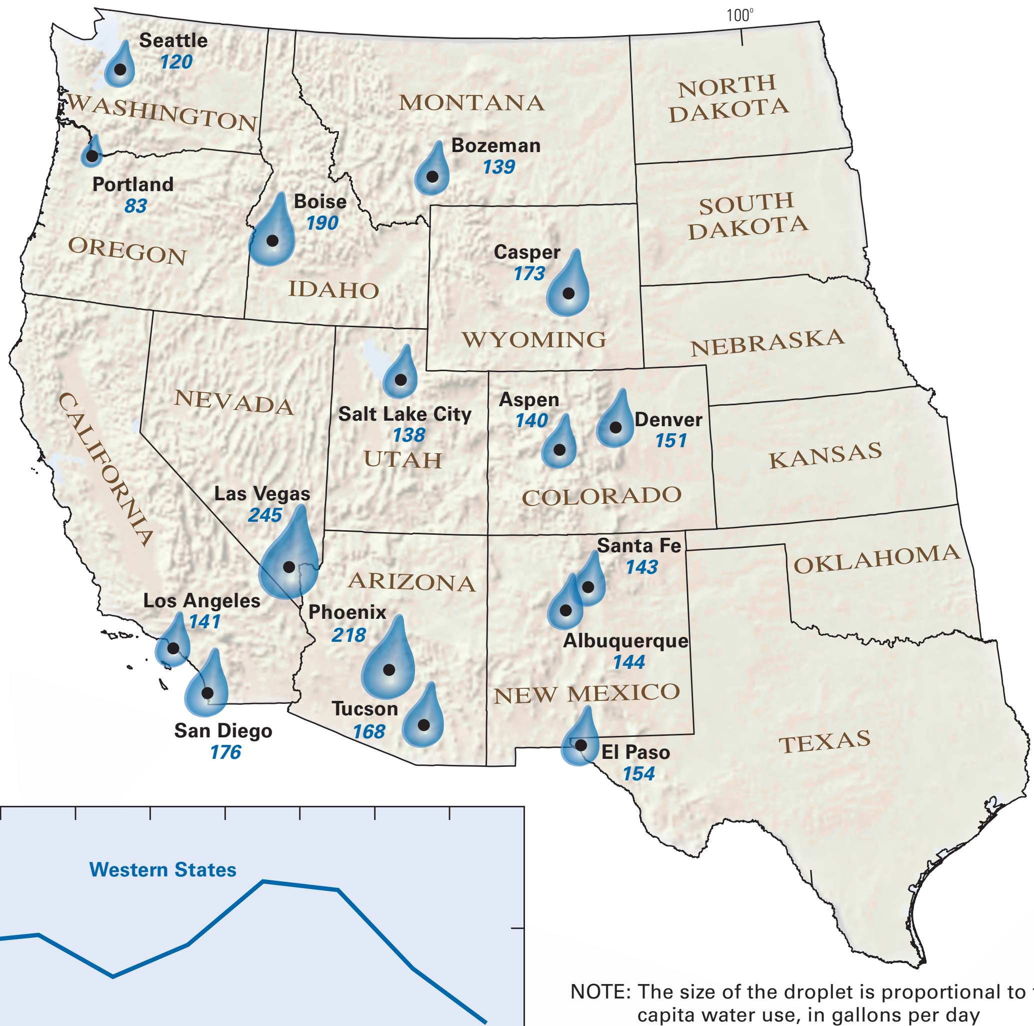
Table 2. *Aquifer-storage change and recharge for the Tucson Basin, 1998–2002, determined by microgravimetric methods.*

[Source: Don Pool, U.S. Geological Survey, Tucson, Arizona, written commun., 2003]

Survey period	Change in storage, in thousands of acre-feet	Recharge (natural), in thousands of acre-feet
1998–1999	66	238
1999–2000	–22	128
2000–2001	–268	0
2001–2002	–23	78

Water-Use Patterns and Distribution

The highest rates of total water use in the United States are in the West— California and Texas (Hutson and others, 2004). Similarly, the highest rates of municipal water use (per capita) also are greater for Western cities that are in the most arid areas (fig. 19). Domestic water use for public supplies in the West averaged 131 gallons per capita day in 2004 (the most recent year for which data are available), as compared to 101 gallons per capita day for the United States as a whole. The trend in public-supply water use has declined slightly since 1985 (fig. 19), but the West consistently exceeds the United States as a whole in per capita water use. If total water use per capita is examined, Idaho is the top water user in the United States—a result of high water use for irrigation with a comparatively small State population (table 3).



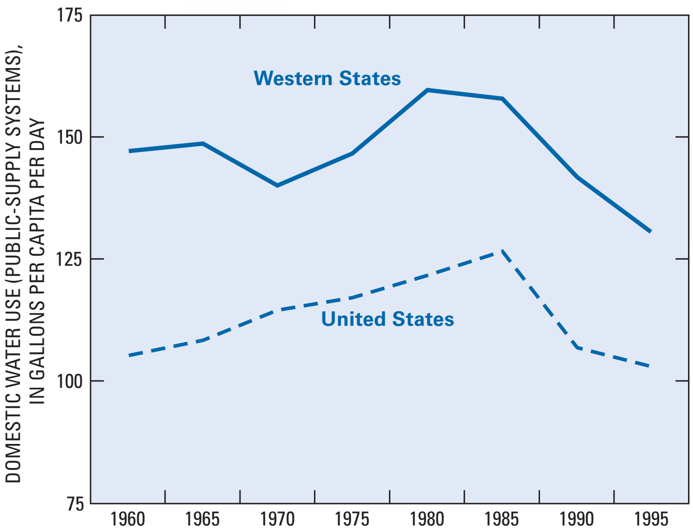


Figure 19. *Per capita water use for selected Western cities (Waldman, 2002) and comparison of average daily per capita water use for the contiguous Western States and the United States for public-supply systems (Solley and others, 1998).*

Urbanization and population growth most often are cited as the major factors applying stress on available water in the West. Trends in water use for the United States, however, reveal that in recent decades, water use has declined or leveled off since the 1980s despite continued population growth (fig. 20; Hutson and others, 2004). Consumptive water use in the United States, when compared to the renewable water supply, shows that more water is being consumed in the Lower Colorado region than is available, which can occur by depleting ground water in storage (fig. 21; U.S. Geological Survey, 1984).

Irrigation is the largest consumptive use of water in the United States, especially in the West. Of the freshwater consumptively used for irrigation in the United States during 1995, 86 percent was used in Western States. Of the 134,000 million gallons of water per day withdrawn for irrigation, 19 percent was lost by conveyance, 61 percent

***Table 3.** Total water use (per capita) for the top 10 States in the United States with total water use and irrigation water use.*

[Data from Hutson and others, 2004]

State	Per capita total water withdrawals, in gallons per day	Total water use, in millions of gallons per day	Irrigation water use, in millions of gallons per day
Idaho	15,100	19,500	17,100
Wyoming	10,000	4,940	4,500
Montana	9,190	8,290	7,950
Nebraska	7,140	12,200	8,790
Arkansas	4,080	10,900	7,910
Colorado	2,930	12,600	11,400
West Virginia	2,840	5,150	0
Kansas	2,460	6,610	3,710
Louisiana	2,330	10,400	1,020
Alabama	2,240	9,990	43

was consumptively used, and 20 percent was returned to surface- or ground-water supplies. California accounts for the largest consumptive use because it has the largest withdrawals of water for irrigation (Solley and others, 1998). When irrigated agricultural lands are retired by home construction, a net reduction in consumptive use of water can be achieved (fig. 22). With the exception of evaporation losses from lawns, gardens, and swimming pools, most of the water used by a household is not consumptively used, but rather is returned to streams or aquifers, albeit possibly diminished in quality.

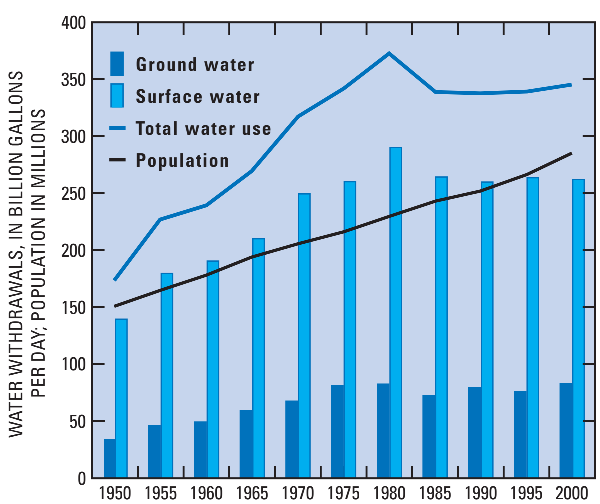


***Figure 20.** Trends in water use compared to population growth for the United States. From Hutson and others, 2004.*

Western Water Law and Federal Reserved Water Rights

The unique circumstances of American expansion into the vast lands of the West gave rise to a body of surface-water law that is markedly different from the laws governing water use in the Eastern United States. Under the riparian doctrine, which is used in the Eastern States, the water-right holder must own land adjacent to a water body. In the West, a water right can be held by a property owner irrespective of the proximity of his land to water, so long as the water is being put to a beneficial use. Western water law, or the prior appropriation doctrine, can trace its origins to the placer gold mines of California and the cultural differences and attitudes of the early settlers. The Mormons, Native Americans, and Spanish settlers all existed in the West, using an approach to water use very different than prior appropriation; but to encourage the westward expansion of the United States, prior appropriation served a useful purpose (Glennon, 2002).

The course of water-rights law was changed in the late 1840s when thousands of fortune seekers flocked to California following the discovery of gold in the gravels of the American River. Water development proceeded on a scale never before witnessed in the United States as these "forty-niners" built extensive networks of flumes and waterways to work their claims. The water carried in these systems often had to be transported far from the original river or stream. The self-governing, maverick miners applied the same "finders-keepers" rule to water that they did to their mining claims—it belonged to the first miner to assert ownership. It allowed others to divert available water from the same river or stream, but their

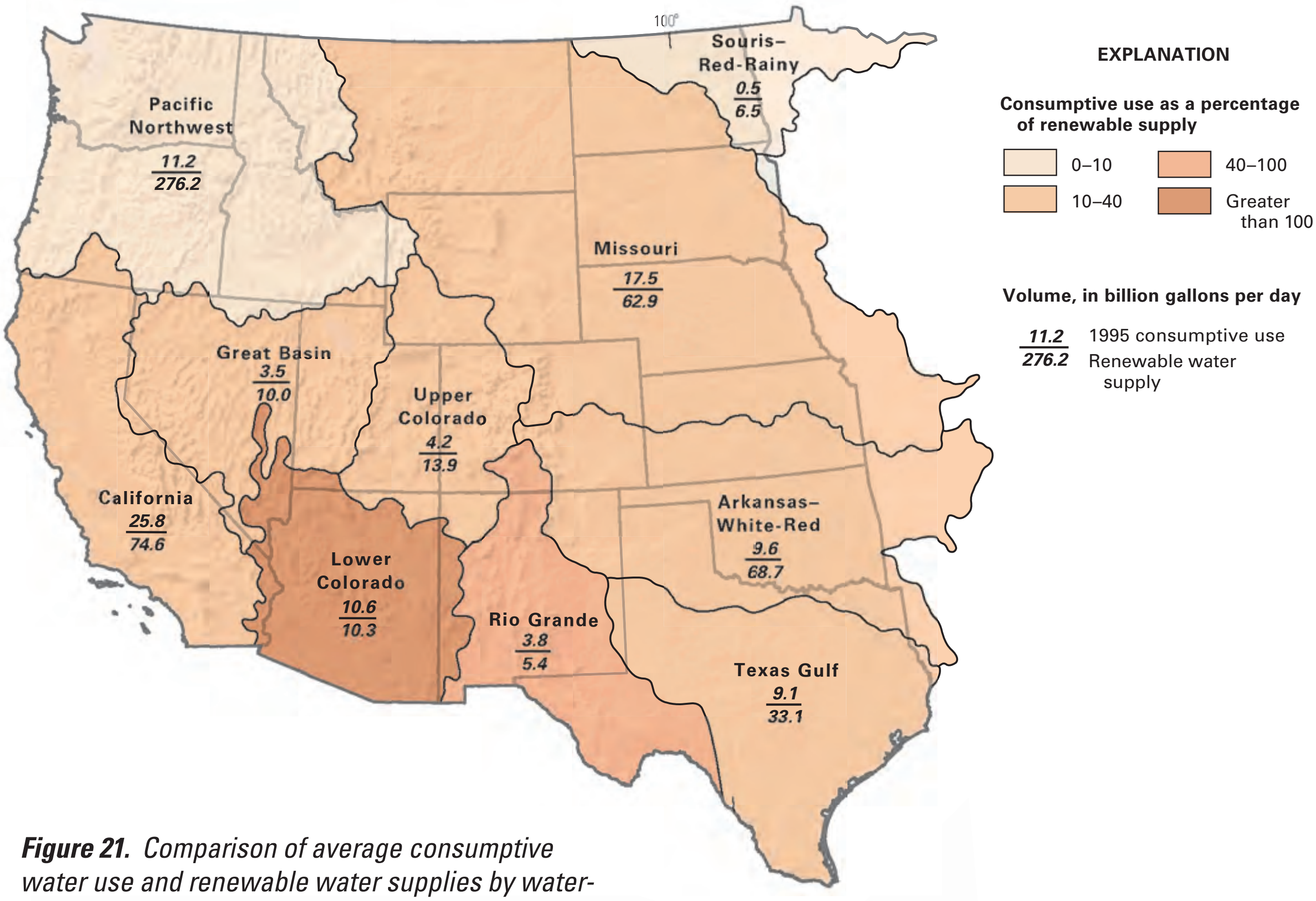


Figure 21. *Comparison of average consumptive water use and renewable water supplies by water-resource region of the contiguous Western United States. (Source: U.S. Geological Survey, 1984; updated using estimates of water use for 1995.)*

rights existed within a hierarchy of priorities. This "first in time, first in right" principle became an important feature of modern water law in the West (Sax and others, 2000).

Western water law historically has placed a higher value on water being used offstream. As an example, the Constitution of the State of Colorado states the following: "The right to divert the unappropriated waters of any natural stream to beneficial uses shall never be denied." Notice the requirement that the water be put to beneficial use. If a diverter fails to use his full allocation of water, after some period of time, he can be forced to forfeit some or all of his right. In this way, the prior appropriation doctrine discourages conservation, for there is a serious disincentive to conserve water on the part of the water-right holder. Such provisions, established in law and set by historical precedent, make it difficult to change the allocation of water to other uses, such as instream use for aquatic life and habitat maintenance and enhancement.

The management of water and the system of issuing water rights is a State responsibility, rather than a Federal one. Although Western water law has its origins in the prior appropriation doctrine, some changes have occurred over time. Today, many aspects of Federal law intrude into this State-based system of water management. The Endangered Species Act, the Clean Water Act, and the Wild and Scenic Rivers Act are just a few of the Federal laws that impinge upon State authority. As an example, the legal concept of Federal-reserved water rights was thought to apply only to Indian reservations until the mid-1970s when the U.S. Supreme Court issued its ruling in the case of *Cappaert* v. *United States*, 1976:

> *This Court has long held that when the Federal Government withdraws its lands from the public domain and reserves it for a Federal purpose, the Government, by implication, reserves appurtenant water then unappropriated to the extent needed to accomplish the purpose of the reservation. In doing so the United States acquires a reserved water right in unappropriated water which vests on the date of the reservation and is superior to the rights of future appropriators.*

The quantity of the water is limited to the quantity needed to accomplish the purpose(s) of the reservation. A significant challenge today is to determine the amount of water required to sustain native peoples, a riparian system, or an endangered species.

Under this ruling, the Federal Government can claim a volume of water, required to sustain the lands set aside (reserved) from the public domain for a particular purpose, with an early priority date. National forests, national parks, national wildlife refuges, and wild and scenic rivers are inferred to have a water right that goes along with the land.

Water Quality

Water for most human use is expected to be of sufficiently good quality to meet the standards of the intended use. In some parts of the West, water may be available in sufficient quantity, but the chemical quality often limits its use. Water from streams and aquifers throughout the West is intensively used and reused for agricultural, mining, industrial, and municipal purposes—each use contributing inorganic, organic, or microbiological contaminants in returns flows. The key water-quality issues limiting water usability in the West are the presence of elevated concentrations of naturally occurring constituents, irrigation return flows, mining, and urbanization. Constituents of concern include salinity, nutrients, trace elements, trace organic compounds, and pesticides.

Naturally Occurring Constituents

Throughout arid regions of the West, the presence of dissolved inorganic salts (dissolved minerals) most widely limits the use of surface water and ground water. Water is an effective natural solvent that dissolves minerals as it interacts with soil and geologic materials on the land surface and within an aquifer system. Deep aquifers represent significant untapped water resources for the West. The geochemical processes that occur under extreme temperatures and pressures over centuries,

Figure 22. *Urbanization in the Salt River Valley near Phoenix, Arizona. Urbanization often retires agricultural land, which results in a net reduction in water use because household and other urban activities consume less water than irrigated agriculture. Photograph by Bert Duet, U.S. Geological Survey.*

however, have increased the levels of salinity in most of these deep waters to that of seawater. Interactions between surface water and ground water also control natural levels of salinity in streams and reservoirs. In many parts of the arid West, saline aquifers and thermal springs are major sources of base flow of streams.

The region's characteristically high evaporation rates also increase salinity. These natural processes are best illustrated by Utah's Great Salt Lake, the largest surface-water body in the West, where salinity ranges from 5 to 25 percent by weight or 50,000 to 250,000 milligrams per liter. For comparison, the salinity of the oceans is about 3.5 percent or 35,000 milligrams per liter of total dissolved solids. Saline lakes, such as the Salton Sea and Mono Lake in California, are found in several closed basins in the West. Many more closed basins are dry lakebeds or playas such as Death Valley, California; Willcox Basin, Arizona; and the Bonneville Salt Flats in Utah.

Trace elements also can occur naturally in water as part of the weathering process at levels that limit water use unless expensive treatment technology is applied. Recently, national public health concern has focused on the presence of natural arsenic in ground water used for drinking purposes. A national study of arsenic in ground water conducted by the USGS revealed that high concentrations of arsenic were in samples from Western counties (Welch and others, 2000; fig. 23).

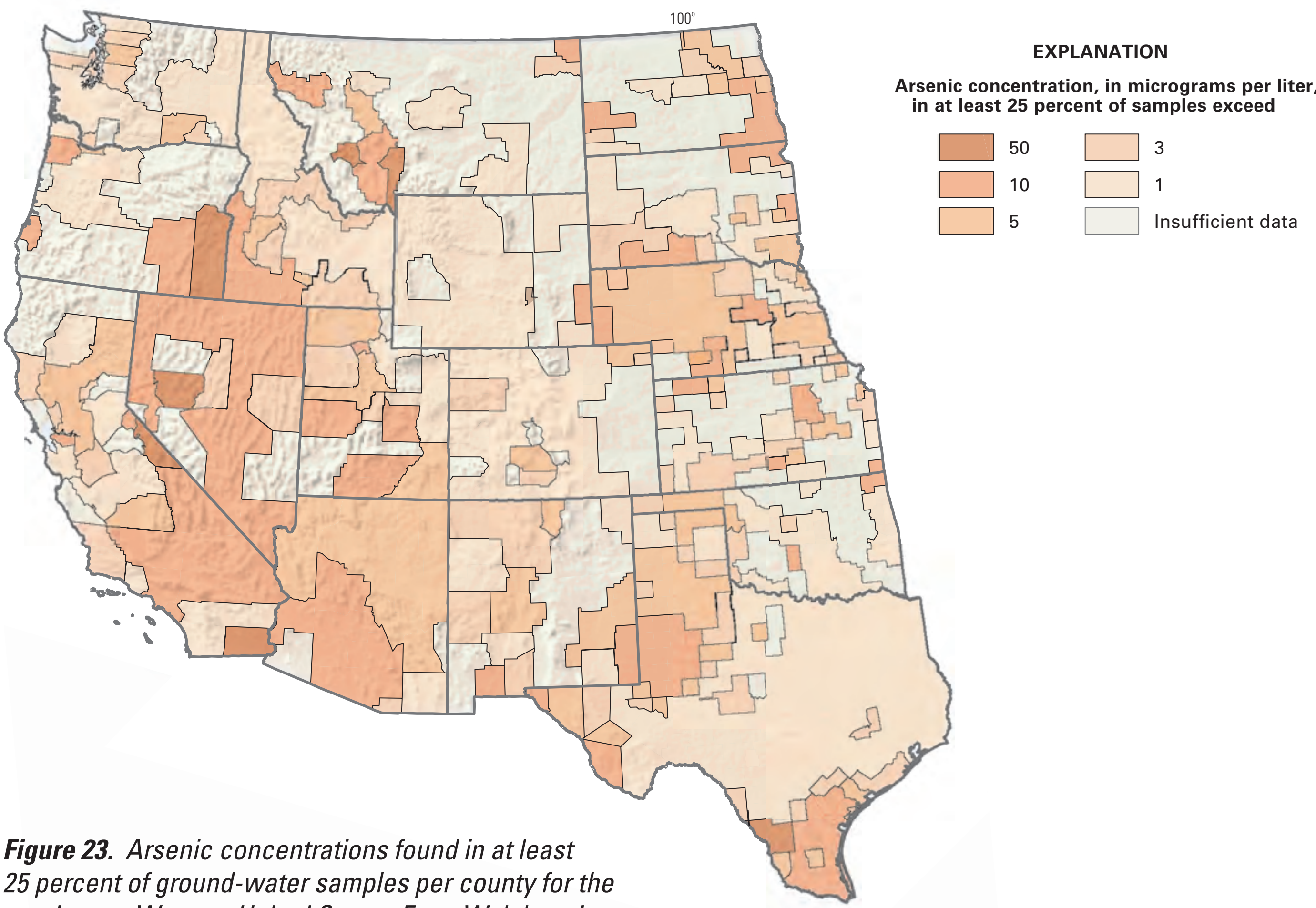


Figure 23. *Arsenic concentrations found in at least 25 percent of ground-water samples per county for the contiguous Western United States. From Welch and others (2000). The current (2004) U.S. Environmental Protection Agency's Maximum Contaminant Level for arsenic in drinking water is 50 micrograms per liter, but will be lowered to 10 micrograms per liter January 23, 2006 (U.S. Environmental Protection Agency, 2001).*

Effects from Irrigation Return Flows

Irrigation drainage can concentrate salts and trace elements in irrigation water by evaporation, leach salts and trace elements from soils, as well as transport excess agrochemicals, such as nitrate and pesticides, to ground water and receiving streams, lakes, reservoirs, and wetlands. In the more highly developed irrigated areas where most of the water comes from a surface supply, as along the Rio Grande from the San Luis Valley in Colorado to Fort Quitman, Texas, and along the Gila River and its tributaries in Arizona, the drainage water returned to the stream by the upper irrigation areas is used again for irrigation in the next area downstream. The cycle of use and reuse may be repeated six times or more until the residual drainage is too small in quantity and too saline to have any further value (Hem, 1985, p. 214). The Department of the Interior's National Irrigation Water-Quality Program reported that selenium is the trace element most frequently found in elevated concentrations in irrigation return flows and has been responsible for wildlife deaths and deformities at several Department of the Interior irrigation project areas in the Western United States. Other constituents of concern include boron, arsenic, mercury, and some pesticides (Engberg, 1993). Water-quality studies conducted by the USGS revealed that the highest concentrations of nitrogen occur in streams and ground water in agricultural areas (fig. 24). Extensive herbicide use in agricultural areas (accounting for about 70 percent of the total national use of pesticides) has resulted in the widespread occurrence of herbicides in agricultural streams and shallow ground water (Fuhrer and others, 1999).

Effects from Mining

Mining remains an important industry supporting the economy of the West. The scars of past mining activities, however, remain visible on the Western landscape. There are hundreds of thousands of abandoned mine sites in the West according to the General Accounting Office (1996), and the cost of reclamation is in the billions of dollars. Mining for metals, coal, and other inorganic compounds, such as phosphates and limestone aggregates, can accentuate and accelerate natural geochemical processes. The development of underground workings, open pits, ore piles, mill tailings, and spoil heaps and the extractive processing of ores enhance the likelihood of releasing chemical elements to the surrounding area in elevated amounts and at increased rates relative to unmined areas (King and others, 1995, p. 4). Abandoned, inactive, and active mines (fig. 25) can release mine drainage that is highly acidic and rich in trace elements that are toxic to aquatic communities and humans if consumed. Exposed mine deposits are capable of leaching trace elements as well. Tailings piles and mining roads are a source of sediment that can clog streambeds and adversely affect aquatic habitat, as well as reduce the useful life of reservoirs downstream. Ground-water quality also can be adversely affected by mine development. Restoration of affected streams and aquifers is costly, and residual-mining waste ponds and piles require perpetual maintenance to prevent future damage to riparian habitats and degradation of water quality.

Effects from Urbanization

Many areas of the West are growing rapidly. Such development not only increases the quantity of wastewater return flows that are used downstream or used to recharge aquifers, but also affects the quality of stormwater runoff. Traditional municipal wastewater-treatment technology was not designed to effectively remove many of the pesticides, industrial and household chemicals, and pharmaceuticals that enter the collection system (Kolpin and others, 2002). Recent research also has shown that standard disinfection practices may be ineffective at killing some highly resistant pathogens, including protozoan pathogens, *Giardia* and *Cryptosporidium*, and viruses. Chlorination of water also can produce trihalomethanes, which are undesirable cancer-causing by-products. USGS studies (Fuhrer and others, 1999) revealed that some insecticides commonly used around homes and gardens and in commercial and public areas are widespread in occurrence. These insecticides occurred at higher frequencies, and usually in higher concentrations, in urban streams than in agricultural streams. The use and improper disposal of industrial chemicals have caused large ground-water contaminant plumes in some urban areas. Ground-water contamination is particularly difficult to reverse with present treatment technologies.

Biodiversity and Habitat Change

The wide range of climatic conditions, geography, elevation, and geologic terrain gives rise to great biodiversity in the West. The number of endangered species, however, is disproportionately represented in the Western States. Aquatic ecosystems in the West, particularly in the Southwest, are characterized by the highest rates of endemism (species restricted to a particular location or region) on the continent. In the Colorado River Basin, for example, 35 percent of all native genera and 64 percent of the 36 native fish species are endemic (Carlson and Muth, 1989). Similarly, 30 percent of the fish species in the Rio Grande are endemic. Endemism in Western fish generally reaches its highest level in

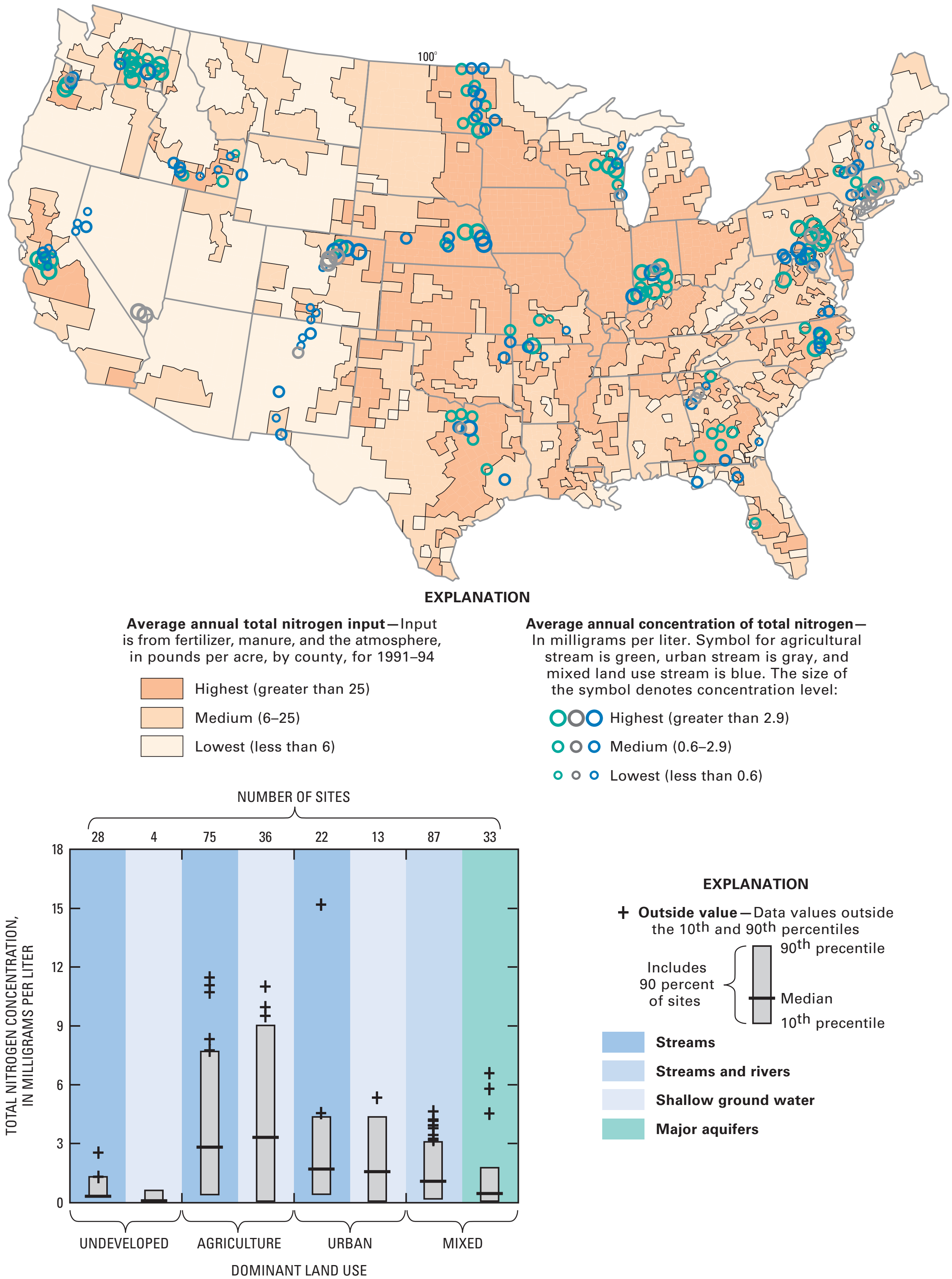


Figure 24. *Total nitrogen concentrations in streams, rivers, and ground water in the contiguous United States. From Fuhrer and others (1999).*

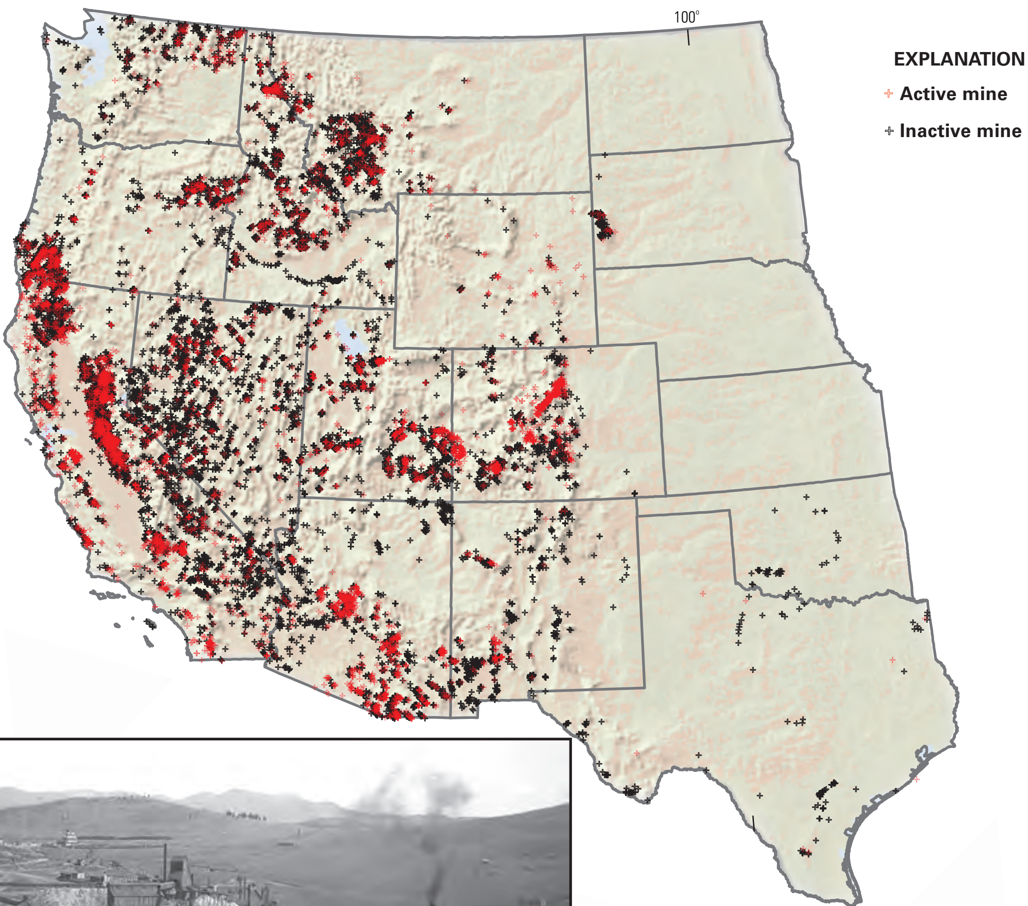


Figure 25. *Active and inactive metals mines in the contiguous Western United States. Photograph depicts 1903 mine operation in Cripple Creek District, Teller County, Colorado. From McFaul and others (2000) and Lindgren and Ransom (1906).*

small systems, such as isolated lakes and desert springs. When species exist only in a single ecosystem or an isolated area, their populations are in greater jeopardy from those threats that may destroy or degrade their habitat. The Southwestern States have some of the highest percentages of threatened (as listed under the ESA) fish fauna—Arizona, 85 percent; California, 72 percent; New Mexico, 30 percent; and Utah, 42 percent (Warren and Burr, 1994). Regionally, more than 48 percent of the fish in the Southwest have been identified as jeopardized, compared to 19 percent in the Northwest and 10 percent in the Southeast (Warren and Burr 1994; Mac and others, 1998).

The most significant manmade hydrologic structures that have contributed to the development of the West are dams. The economic benefits and environmental consequences of dam construction, however, are not unique to the West. Reservoirs are operated to satisfy multiple objectives beyond storing water for future use. They provide for flood control, improved navigation, power generation, recreation, and fisheries and waterfowl habitat, while trapping sediment and improving some water-quality characteristics downstream. Construction of a dam within a previously unregulated watershed can significantly alter natural, preimpoundment streamflow, sedimentation, and water-temperature patterns, while impeding the free migration of anadromous fish to their native spawning areas. Native fish, protected under the ESA, may be threatened by the clear, and usually cold, releases from dams (Collier and others, 1996). Regulation of a river changes the frequency and seasonality of flood events, reduces the peak water elevation and flow volume during high flows, and alters the distribution and nature of downstream sediment deposits and channel characteristics. The change in the preimpoundment, natural-flow regime in parts of the West has enabled less desirable native and nonnative, exotic vegetation to flourish unimpeded, resulting in clogged stream channels and less diverse riparian habitat and associated biological communities. In some areas, nonnative salt cedar (tamarisk) occupies up to 90 percent of the area originally dominated by cottonwood-willow riparian forests (Patten, 1997). Salt cedars are deep-rooted brushy plants, known as phreatophytes, that have spread rapidly throughout the Southwest after introduction in the late 19th century (Robinson, 1965). They effectively out-compete early successional native trees, bushes, and grasses, resulting in an overgrown monoculture. The infestation of salt cedar has been implicated in causing a reduction of streamflow and an increase in salinity wherever it exists but in particular the Rio Grande along its border with Mexico (fig. 26) and in the Pecos River watershed, New Mexico. Current drought conditions in the Southwest have renewed interest in large-scale eradication of nonnative vegetation, especially salt cedar, for water salvage—a concept embraced a half-century ago. Evapotranspiration losses can be reduced by phreatophyte removal, but the evidence is less persuasive that the water saved can be measured as an increase in streamflow or captured for other uses (Culler and others, 1982; Weeks and others, 1987; Welder, 1988). Moreover, tamarisk eradication projects of the past have shown a reinvasion of tamarisk, making the long-term prognosis for eradication success uncertain.

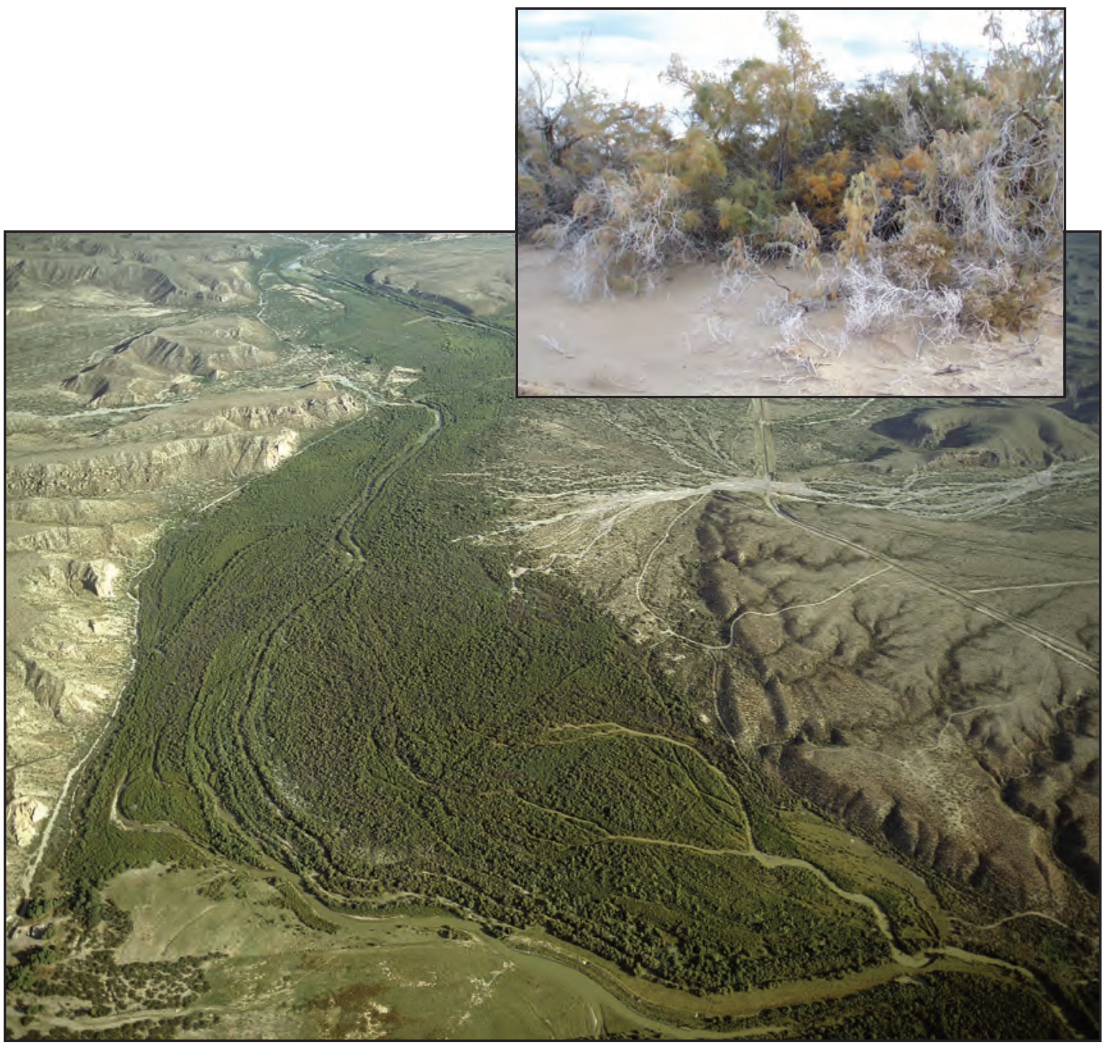


Figure 26. *Salt cedar bosque on the Rio Grande below Fort Quitman, Texas. Photograph by Michael Collier, U.S. Geological Survey. Closeup of Salt Cedar photograph by John Mendelsohn, U.S. Geological Survey.*

Evolving Role of Science

Deeply ingrained in society is the concept that science will deliver a technological solution to the most vexing issues (National Science Board, 2000). The determination of the highest and best use of a resource is becoming more difficult as there are more voices to be heard and society's values are changing more rapidly. Water-resource management will be aided by the proper conduct of science and by the success of communicating scientific information to decisionmakers.

In 1998, the U.S. House of Representatives, Science Subcommittee, proposed a new role for Federal science and technology—environmental decisionmaking.

> *We believe this role for science will take on increasing importance, particularly as we face difficult decisions related to the environment. Accomplishing this goal will require, among other things, the development of research agendas aimed at analyzing and resolving contentious issues, and will demand closer coordination among scientists, engineers, and policymakers (U.S. House of Representatives, Science Subcommittee, 1998).*

The most contentious issues often involve water and how it should be allocated. Water science is not presently well adapted to serve societal needs in this multidimensional water-resources environment (National Research Council, 1991b; Naiman and others, 1995). The Water Science and Technology Board (WSTB) of the National Research Council in its report entitled, "Envisioning the Agenda for Water Resources Research in the Twenty-First Century" (2001a), calls for science and technology to be given a new priority to improve the factual basis for water-resource decisionmaking in the next century (National Research Council, 2001a). One grand challenge is the need to "establish the capacity for detailed, comprehensive hydrologic forecasting, including the ecological consequences of changing water regimes, in each of the primary U.S. climatological and hydrological regions." (National Research Council, 2001b). In this section, the role of science is examined, and how it has changed along with society's demands regarding water development. The use of scientific information in several case examples is examined in greater detail for several of the key scientific challenges facing the phase of sustainable use. The development, use, and management of water in the West has followed an evolutionary path, and water-management strategies have changed over time, reflecting societal values and the unique developmental pressures related to a diminishing supply. The need for and type of scientific information also has changed. During the time the West was being settled, science supported development and the technology of offstream water use. Today, science still supports development, but also is expected to reveal the environmental effects of past actions, predict the environmental consequences of future actions, and define sustainable water-use strategies for the future. The evolutionary phases of water use in the West that science has supported can be discussed as follows: (1) the development and construction phase, (2) the consequences and environmental-awareness phase, and (3) the sustainablility phase.

The transition from one phase to another generally is hastened by water shortage and accompanied by an increasing demand for scientific information, especially the later phases, to provide information in support of water-management strategies that are more sustainable. The scientific data and information needed to support each phase have evolved and grown in complexity and sophistication. For example, there is the recognition that surface water and ground water are in hydrologic connection and may need to be managed more holistically. This awareness is relatively recent in the sweep of history, and the analytical tools necessary to construct unified water budgets and predictive models only now are being developed. There also is a growing interest in integrated water-resources management, which means making decisions in the context of an entire watershed or aquifer system. Scientists are being asked to define and quantify consequences of various water-use scenarios. Furthermore, integrated science is being called upon to better quantify and monitor changes in the hydrologic system, the physical habitat requirements of riparian ecosystems, and the life-sustaining needs of individual species.

Development and Construction Phase

The Hohokam Indians developed irrigation in the Southwest as early as 700 A.D. by diverting water from rivers, in what is now central Arizona, through at least 125 miles of canals to irrigate more than 100,000 acres of beans, squash, and corn. Early European settlers, just as the native people before them, diverted water from streams onto fields for agriculture and also for mining.

The discovery of gold in January 1848 by Joseph Marshall at Sutter's Mill near Sacramento, California, imposed an urgent need for change in the approach and management of water. Irrigated agriculture was a collective enterprise, but gold digging was more individualistic—every man for himself. Water was a critical resource needed to extract placer gold, and demand for water quickly exceeded supply (fig. 27).

Western droughts between the 1890s and the 1930s provided the realization that surface flows are subject to climate variability, and ensuring dependable water supplies became a preoccupation for Western policy-makers. Dams and reservoirs to store water in times of surplus became the widely accepted solution to the vagaries of climate. John Wesley Powell's strategy was "the control of great rivers," which meant trapping the waters near their origins, the melting snowfields in the mountains, to use it for irrigation in the lower valley, and also to protect the valley from destruction (Worster, 2001). Floods were the bane of early settlers, destroying property improvements and crops. After the passage of the Reclamation/Newlands Act of 1902, which allowed the government to undertake irrigation projects to establish farms for relief of urban congestion, construction of dams and water-delivery systems began and proceeded in

Figure 27. *Esperance Hydraulic mine near French Corral, Nevada County, California, 1909. Placer mining for gold removes water from the stream channel. From Gilbert (1917).*

earnest after the droughts of the 1930s. Water was delivered from the reservoirs to the expanding irrigated acreage and growing municipalities by canals and aqueducts. The Federal government's role in water works expanded greatly nationwide in the aftermath of the 1927 floods in the Mississippi River Basin (Barry, 1997).

The most pressing need for scientific information during the early phase of development was a means of quantifying flow, which is still important today. One needed to compute the volume of water being claimed under a given water right and be able to administer those claims in practice at the stream, so a system of measuring flow was first developed to support the miners, hence the term "miner's inch" (equivalent to 0.025 cubic foot per second)—the volume of water that would flow through a 1-inch-square orifice under a given head. To administer the irrigation system, the unit of measure developed by Powell and the early USGS was the acre-foot—the volume of water covering 1 acre of land to a depth of 1 foot. There were few concerns for other uses of water or the effects of diversions; early users were content to just measure the flow and divide it up. A brief history of water development for each State is provided in the National Water Summary—1987 (Carr and others, 1987).

Franklin D. Roosevelt's New Deal of the 1930s linked programs of public works and reclamation projects for flood control with the development of electrical power generation capacity. The Flood Control Act of 1944 broadened the authorities and mission of the Federal Government. The Bureau of Reclamation (Reclamation), U.S. Army Corps of Engineers, and Tennessee Valley Authority were authorized, and subsequently appropriated funds were used to build dams for flood control and hydropower generation throughout the Nation. In the National Inventory of Dams (U.S. Army Corps of Engineers, 2001), there are about 77,000 dams listed that are higher than 6 feet and impound at least 15 acre-feet of water, an estimated 7,700 majors dams (3,610 in Western States) that are higher than 50 feet and impound 5,000 acre-feet of water or more (fig. 28), and hundreds of thousands more that are smaller than the criteria stated above. Since 1985, little reservoir capacity has been added in the United States, signaling the conclusion of the dam-building era (fig. 28).

The collection and interpretation of scientific information useful to support reservoir construction and development was complex. Engineers required continuous-record streamflow and precipitation gages to collect the data needed for the design and management of the new reservoirs. Methods were developed to estimate flood frequencies and flow-duration curves to help evaluate risks. There was concern that reservoirs would fill with sediment, thereby shortening their useful life expectancy, so methods of collecting sediment data and estimating deposition rates were developed. Methods to estimate seepage and evaporation from reservoirs were needed to determine losses, especially from large surface-area reservoirs in the Southwest. With time, some reservoirs developed water-quality issues, which affected consumption of the water owing to taste and odor issues. Thus began the collection of water-quality and biological data within these reservoirs and their watersheds. These data were used to begin to develop a scientific understanding of physical, chemical, and biological processes within reservoirs and relations needed to support experimentation with alternative operational strategies.

Interest in ground water initially focused on springs, particularly in the arid West. Emigrant trails linked many springs, which served as watering holes for people and livestock. Native Americans and European settlers dug shallow wells by hand to secure clean drinking water, especially if a higher elevation spring was not available. These wells provided domestic water from less than 30 feet in depth and typically were located in the sand and gravel along the streams. Advances in well drilling, pump technology, and rural electrification allowed the broad-scale development of ground water in the Western States beginning in the early 1900s. Large-scale ground-water development for irrigation spread throughout the West, especially after World War II.

Because ground water as a resource was less understood than surface water and administered separately, few constraints were placed on well drilling and ground-water pumping by the States, at least initially. Regional aquifers near population centers and areas of intensive agriculture were developed and subsequently depleted in less than a century (fig. 29). There are an estimated 16 million water wells in the United States, of which 283,000 are public-supply wells with distribution systems (National Ground Water Association, 2003).

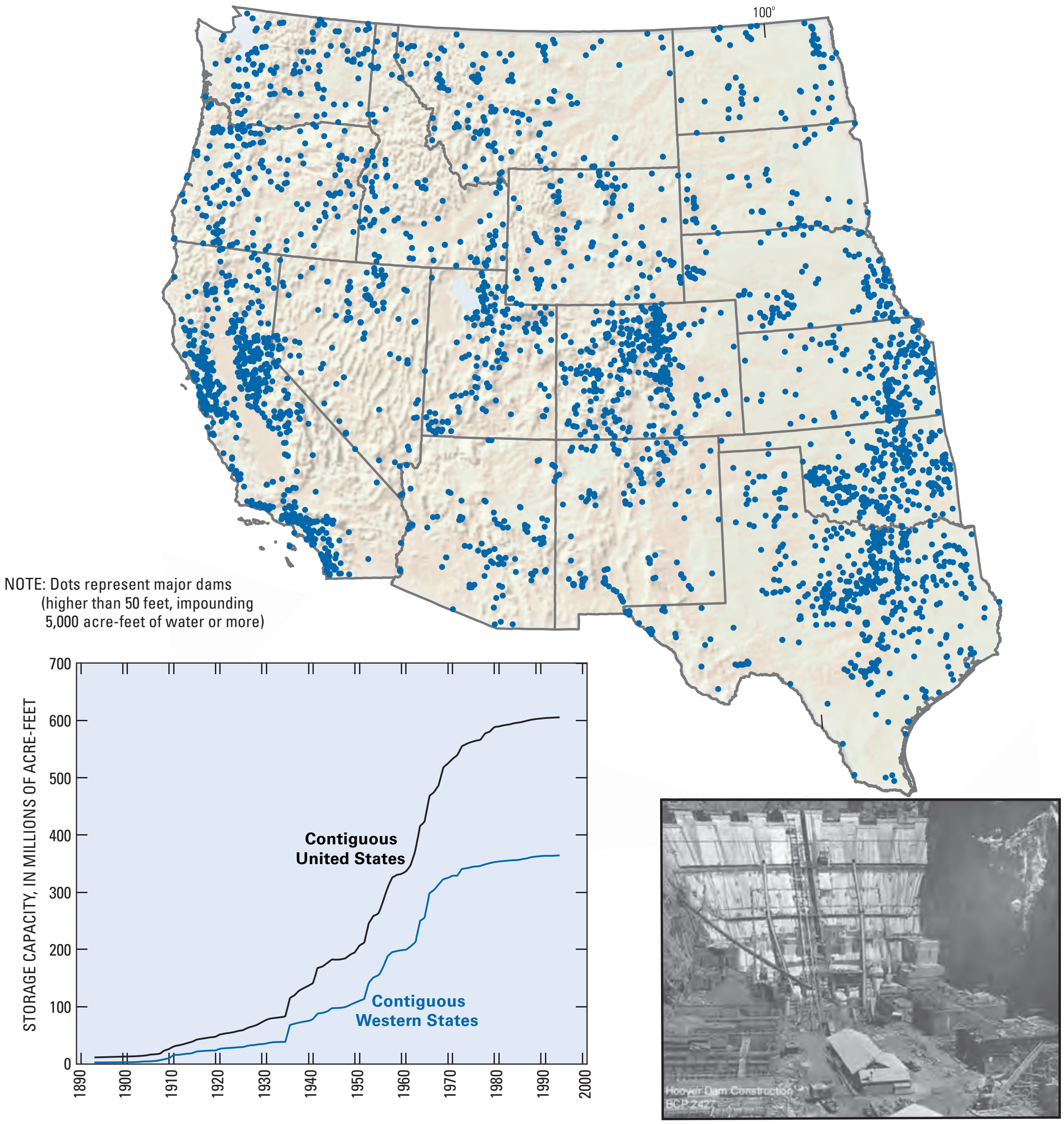


Figure 28. *Total surface-water reservoir capacity in the contiguous Western States and the contiguous United States from 1894 to 1994, and location of major dams in the Western States. Photograph of the construction of Hoover Dam on the Colorado River. From U.S. Army Corps of Engineers, National Inventory of Dams (2001).*

The lack of a basic understanding of the potential yield that could be expected from a well of a given depth and method of completion limited Western development. This demand for information gave rise to the formal discipline of ground-water hydrology, which had its beginnings in the mid-19th century. To support this growth in ground-water exploration, reliable methods were developed to accurately measure and interpret water-level data to determine the rate and direction of ground-water movement, to assess geologic controls on artesian aquifers, and to measure in the laboratory or in the field aquifer physical properties and hydraulic characteristics, such as porosity, permeability, and transmissivity. Scientists in academia and the USGS would use these data to relate well yield and water-level drawdown more closely to aquifer

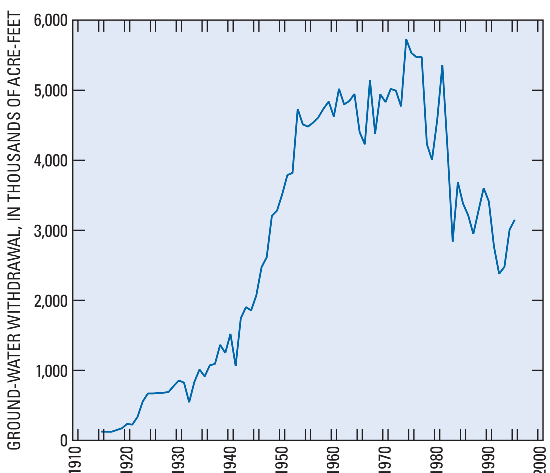


Figure 29. *Annual ground-water withdrawals in Arizona. (Source: Arizona Department of Water Resources and U.S. Geological Survey.) Photograph of well drilling near Flagstaff, Arizona, U.S. Geological Survey (1950).*

properties, which ultimately contributed to the development of predictive equations to estimate pumpage rates for new wells. They also learned how to interpret the streamflow data being collected to estimate ground-water recharge and ground-water discharge to streams, which represented the initial development of methods to assess ground-water/surface-water interactions and conjunctive use.

Consequences and Environmental-Awareness Phase

Many benefits have ensued from the construction of dams and the development of ground water: water supply, irrigation, flood control, improved navigation, power generation, recreation, fisheries and waterfowl habitat, and improvement in some water-quality characteristics downstream. With time, however, undesirable changes in the environment emerged as the result of water development. Alterations in the annual flow regime, patterns of sediment transport and deposition, and water-temperature conditions, to note a few, in turn produced changes in flora and fauna in the riparian environment. Some effects put native fish in danger of extinction while other changes created welcomed opportunities, such as salmon fishing on the Northern Great Plains in Lake Oahe. The changes in flora and fauna brought about by reservoir construction and dam operations are now of concern on all the major rivers of the West. In fact, the management of the major Western rivers and reservoirs in some cases is dominated by endangered species concerns (fig. 30).

Today, the surface waters of the United States are developed largely throughout the West. Little opportunity remains to increase storage along main-stem rivers because few suitable sites remain for dams, and there is general concern about the environmental effects of impoundments. The surface waters of the Nation also receive and assimilate, to some degree, significant quantities of point- and nonpoint-source contaminants. In contrast, ground water is still under active development. According to the National Ground Water Association (2003), there are approximately 800,000 boreholes drilled for water in the United States each year. Although not all boreholes are completed as wells, this represents a substantial degree of ground-water development. The consequences of pumping ground water can include depletion of water stored in the aquifer, poorer quality ground water supplied to wells, diminished flow to springs and streams, and land subsidence. The challenge for science has changed from supporting the development of water resources to understanding the consequences and environmental effects of the various water-use strategies. A few of the large-scale examples of the consequences of the water development in the United States—conversion of rivers to reservoirs, ground-water and surface-water interactions, land subsidence, and changes in water quality—are discussed in the following sections.

By the mid-1900s, the public became aware that ground water, like other natural resources of the West, was finite and exhaustible. States began to manage ground-water resources more actively, alter administrative

Figure 30. *Selected endangered species that strongly influence the management of Western rivers. Fish images drawn by Joseph R. Tomelleri at americanfishes.com.*

rule, and implement some type of monitoring programs for most aquifers in the West. For example, Arizona enacted the Groundwater Management Act of 1980, which created Active Management Areas (AMAs) with the goal of achieving “safe yield” for ground-water use. Safe yield is achieved under the law when ground-water withdrawals are equal to or less than estimated ground-water recharge from all sources, natural and artificial.

California does not have a statewide management program or permit system to regulate appropriation of ground water; however, some counties and ground-water districts have implemented regional regulation practices. The California Supreme Court rejected the English Common Law system of absolute ownership of ground water, which essentially had allowed for unregulated pumping of ground water. Instead, the court adopted the rule of “reasonable use of percolating waters.” This holding established the concept of an overlying right (similar to a riparian right) that entitles those who own land above an aquifer to make reasonable use of the ground water underlying that land (California Environmental Resource Evaluation System, 2002).

Conversion of Rivers to Reservoirs

The Nation’s rivers are an important component of the natural environment and economic infrastructure. They are crucial water supplies for municipal, industrial, and agricultural uses and are sources for recreation, power generation, and transportation of goods. The history of water policy in the United States is dominated by the construction of structures such as dams, canals, dikes, and reservoirs (Gleick, 2000). The 77,000 dams in the United States were constructed largely without considering the environmental consequences. The dams on the Columbia River, for example, were constructed without the full understanding of the long-term consequences to anadromous fish populations. When Glen Canyon Dam was proposed for the Colorado River, few concerns were expressed about the downstream ecosystem. The environmental debate focused on the submergence of Glen Canyon’s sculptured canyon walls beneath what is now Lake Powell in Utah. Today, the management of Glen Canyon Dam is influenced strongly by numerous factors downstream from the dam, such as preservation of the limited sand supply that maintains beaches for recreation and wildlife habitat, and protection of the Kanab ambersnail and the humpback chub (Bureau of Reclamation, 1995).

The storage, diversion, use, and reuse of the limited water resources to support agriculture, industry, and the expanding human population in the West have had an adverse effect on the health and sustainability of aquatic biological communities and associated riparian and wetland habitats (Postel and Richter, 2003). Some examples of adverse effects include:

- Loss of ecologically significant wetlands and other riparian habitat and invasion of less desirable native and nonnative, exotic vegetation owing to reduced flooding and increased ground-water pumpage. Riparian habitat, such as that along the Pecos River in New Mexico and Texas, supports more than 75 percent of the animal species in arid regions during some stage of their life cycles and is the sole habitat for amphibians and invertebrates that require moist conditions (Patten, 1997).
- Changes in the saltwater-freshwater interface in coastal estuaries, such as those in the San Francisco Bay in California, and the ecosystems dependent upon them.
- Coastal land subsidence, such as that in the Houston-Galveston area of Texas, caused by subsurface fluid extraction.
- Contamination of fish and wildlife and their habitats as a result of irrigation return flows, urban runoff, point-source discharges, and numerous abandoned mine drainage areas in Colorado and South Dakota.
- Reduced populations of anadromous fish owing to instream restrictions to migration, such as those in the Columbia River in Oregon.
- Extinction or near-extinction of native fish species, as in the Upper Klamath Basin in Oregon and California, resulting from habitat degradation.
- Increased streambank erosion associated with loss of bank-stabilizing riparian vegetation in numerous urbanized locations throughout the West.

The U.S. Fish and Wildlife Service and Federal courts are using authorities under the ESA to divert water from past economic-based uses to support sensitive ecological communities and their habitats. The competition for water in the arid West, however, was intense well before considerations were being given to ecological water needs. An analysis of instream water needs showed that instream flows in the Rio Grande, the Upper Colorado, and the Lower Colorado water-resource regions are insufficient to meet current needs for wildlife and fish habitat, much less allow for any additional offstream use (Guldin, 1989).

> ***"Serious troubles are arising in the Rio Grande Valley. The valley is all aflame."***
> **—John Wesley Powell, circa 1890**

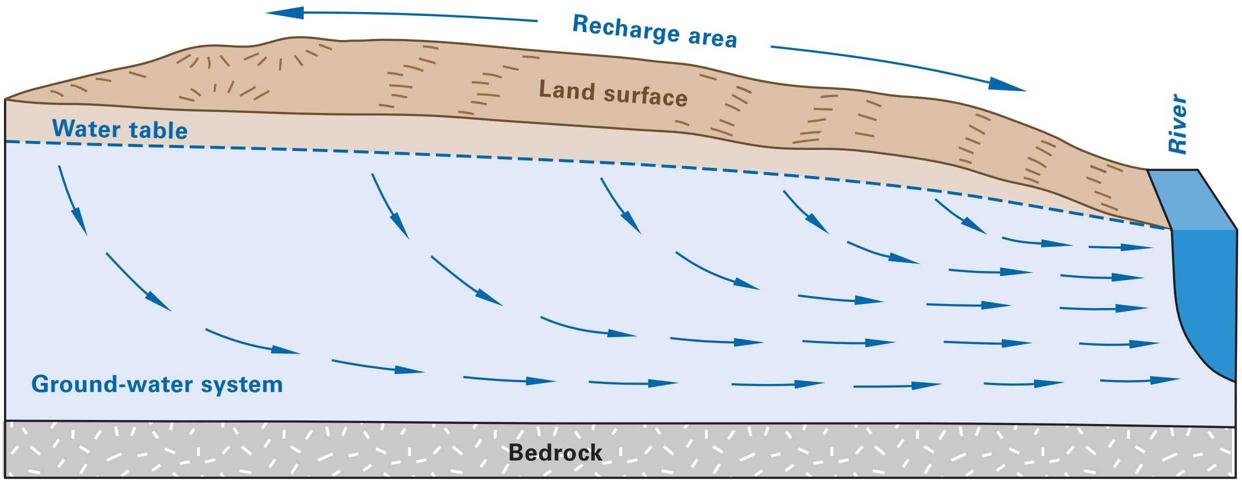
Dam removal, as an environmental-restoration measure, has gained legitimacy in recent years. The Aspen Institute (2002) published a report entitled, "Dam Removal: New Options for a New Century." More than 400 dams have been removed in the United States since the 1920s (Pohl, 2000). Environmental groups, such as American Rivers, Trout Unlimited, and Friends of the Earth, support dam removal when certain criteria are met. American Rivers administers a program in cooperation with the National Atmospheric and Oceanic Administration to provide funds for dam removal to enhance fish passage. In the future, decisionmakers will demand accurate and unbiased scientific information when considering dam removal or remedial measures to minimize adverse environmental effects owing to the operation of dams. The effects of dam operation and reservoir management on watershed ecosystems will need to be addressed. As freshwater is fully utilized, the evaporation losses from reservoirs, particularly in arid climates, may become a less affordable component of the water budget.

Ground-Water/Surface-Water Interactions

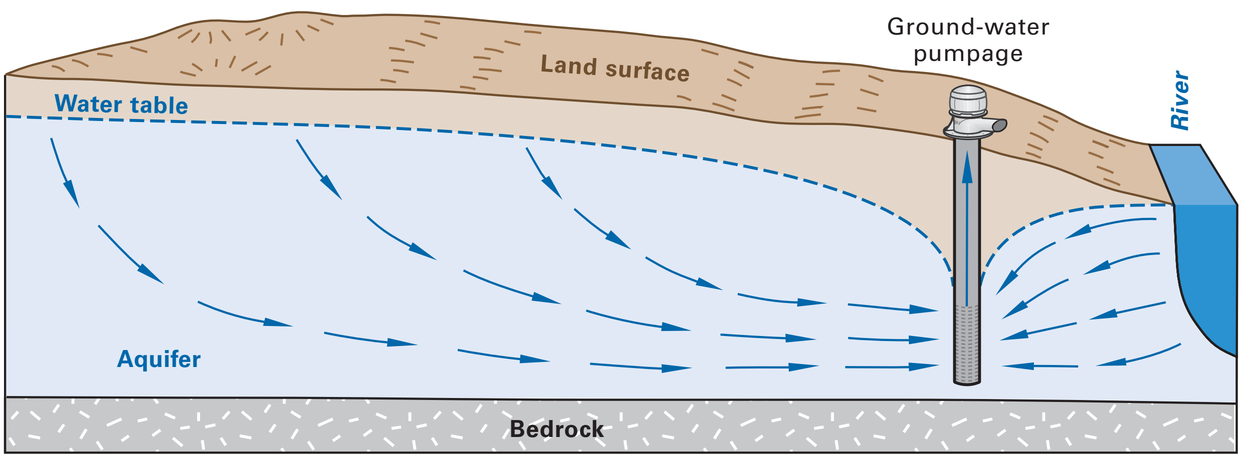
Surface water and ground water have been historically thought of as separate resources and often are managed separately. As the hydrologic sciences have matured, the details of how surface water and ground water interact as a single resource are becoming better understood (Winter and others, 1998). Water-level declines in aquifers can produce a corresponding decline in a lake or diminish or cease the flow to springs. Ground water is an important component of flow in many streams, often sustaining base flow. Streams also are an important source of recharge for aquifers. Pumping can diminish ground-water flow to streams and, in some cases, can reverse the direction of flow, which causes water to flow from the stream into the aquifer (fig. 31; Alley and others, 1999).

In the case of the Rio Grande, the surface flows are used and reused along its way from the mountains of Colorado to the Gulf of Mexico. Ground water from the aquifers adjacent to the Rio Grande is the sole source of drinking water for Albuquerque, New Mexico, and Ciudad Juarez, Mexico, and provides about one-half the drinking-water supply for El Paso, Texas. Without sufficient flow in the Rio Grande to provide recharge, these vital aquifers cannot sustain pumping. (For additional information on the Rio Grande, see Box C.)

A more visible example of the effects of ground-water pumping on surface water is the situation of the Santa Cruz River near Tucson, Arizona. Pumping from the regional aquifer has caused water levels to decline beneath the river during the last century. The lush vegetation in the riparian zone along the river died back and was gone by the 1980s—deprived of the once shallow water table (fig. 32). The river channel also has widened, and the bed of the river now is shifting sand, which has made the reestablishment of vegetation difficult.



A. Natural conditions



B. Change in equilibrium caused by ground-water pumping

Figure 31. *Effects of ground-water pumping on flow to streams. A, Natural conditions. Recharge to the aquifer is equal to ground-water discharge to the stream. B, Change in equilibrium caused by ground-water pumping. Pumping the well begins to draw water from the stream, decreasing discharge to the stream. From Alley and others (1999).*

Additional Information on the Rio Grande

The Rio Grande is the lifeline for an arid landscape that stretches from New Mexico through Texas to the Gulf of Mexico. The river is expected to support diverse and fragile ecosystems while at the same time supplying water for expanding urban centers, industrial complexes, and long-standing agricultural uses in the Southwestern United States and northern Mexico. Underlying the river are regional alluvial aquifers that are the exclusive source of drinking water for Ciudad Juarez, Mexico, and Albuquerque, New Mexico, and about one-half of the water supply for El Paso, Texas. These critical aquifers and the river are in direct hydraulic connection, operating as a single water resource—infiltration of the river water recharges these aquifers and, in turn, the aquifers provide life-sustaining base flow in the river. During the past century, however, the large number of diversions from the fully appropriated Rio Grande have affected the availabilility and areal distribution of water that recharges these aquifers. For example, in 1968, the reach of the Rio Grande between the central business districts of Cuidad Juarez and El Paso was transformed into a lined canal, which now prevents recharge from the river to the ground-water system along that reach. This decreased recharge exacerbated the effect of increased ground-water withdrawals by increasing the rate of ground-water-level declines (Land and Armstrong, 1985). River diversions, reduction in recharge, and increased ground-water pumpage have significantly affected the sustainability of base flow in the river, which supports highly sensitive riparian habitats and native species, such as the endangered Rio Grande silvery minnow.

Rio Grande at Belen, New Mexico. Photograph provided by the U.S. Geological Survey.

Rio Grande silvery minnow (drawn by Joseph R. Tomelleri at americanfishes.com).

Computer simulations of the Santa Fe aquifer system in Albuquerque using a USGS-constructed ground-water flow model revealed that the quantity of water available for municipal supply was significantly less than previously estimated (Kernodle and others, 1994). Well-defined cones of depresssion near pumping centers and regional water-level declines also have been mapped. These declining water levels could adversely affect the long-term use and sustainability of the aquifer system, potentially resulting in deterioration of water quality, land-surface subsidence, and increased pumping and well-installation costs. The ground-water flow model will be used to reliably estimate the effects of ground-water withdrawals on flow in the river to support conjunctive management of the region’s water resources.

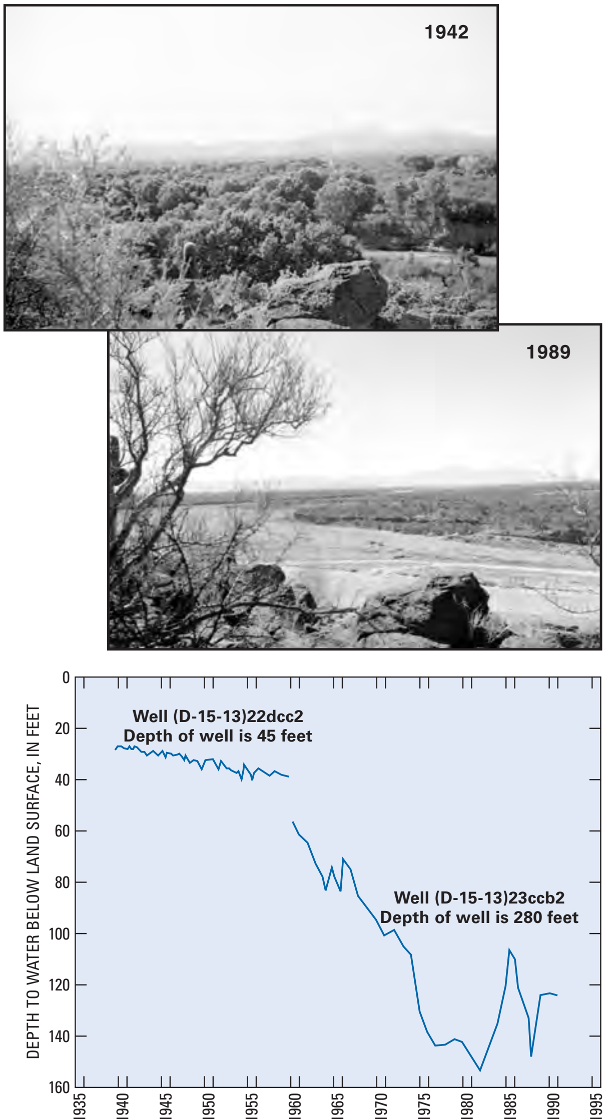


Figure 32. *Change in riparian vegetation along the Santa Cruz River, Tucson, Arizona, as the result of water-level declines in the regional aquifer. Photographs of the Santa Cruz River looking south from Tucson, Arizona, provided by Robert H. Webb, U.S. Geological Survey.*

Land-Surface Subsidence

In many areas of the West, land-surface subsidence, the gradual lowering of the Earth's surface, is an often overlooked environmental consequence of land- and water-use practices (Galloway and others, 1999). The principal causes of subsidence nationwide are aquifer-system compaction caused by extensive ground-water pumping, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost (National Research Council, 1991b). The Santa Clara and San Joaquin Valleys, the Ventura area of California, the Houston-Galveston area of Texas, the Las Vegas area of Nevada, and several areas in south-central Arizona are particularly afflicted by this geohazard (fig. 33). The approximate maximum subsidence (as of 1997) for selected locations in the West is listed in table 4.

Land-surface subsidence also can cause reduction in aquifer-system storage that can be irreversible. The volume displaced between the current and previous land-surface elevations is proportional to the reduction in aquifer-system storage and the volume of water removed. In the San Joaquin Valley of central California, such vast areas have subsided that it is said to be the largest alteration of the Earth's surface ever caused by human activities. Most subsidence in the Nation is a consequence of the exploitation of ground water, and the increasing development of land and water resources threatens to exacerbate existing land-subsidence issues and initiate new ones (Galloway and others, 1999).

Changes in Water Quality

As the settlement of the West progressed and towns became cities, other water-quality issues began to emerge. The disposal of wastewater became hard to ignore, and newly synthesized chemicals were introduced into the environment. Scientific investigations promoted an awareness of the unintended consequences of manmade chemicals in the environment. Advances in chemical analytical methods made it possible to detect compounds in minute concentrations.

Wastewater Disposal.—The treatment of human waste was not a consideration in the early development of the West's water resources. Drains were constructed to collect untreated human waste and divert it to lagoons or directly into an adjacent stream. The wastewater was diluted and instream processes converted the oxygen-demanding waste into biodegradable compounds. Streams have a "finite" self-purification capacity for assimilating organic waste loads. When this natural capacity was exceeded, the stream would become anoxic, emitting a fowl stench and causing fish kills. The concerns expressed initially were not for public health, but about the water being unsuitable for agricultural uses. Not until science associated contaminated water to disease in the late 19th century was the water from these contaminated streams identified as being unsafe for direct human consumption.

Over the subsequent decades, there has been a major Federal, State, and local investment in a wastewater-treatment infrastructure. Methods were developed to describe the physical and chemical

Figure 33. *Land subsidence in the Eloy area, central Arizona. Photograph provided by the U.S. Geological Survey.*

characteristics of wastewater and receiving ambient waters, and to quantify the mixing and reaeration characteristics of flowing streams. With this information, predictive equations were developed to estimate the amount of oxygen-consuming waste that could be safely discharged while maintaining a minimum dissolved-oxygen concentration in the receiving streams.

Treatment of the Nation's municipal and domestic water supply has played an important role in reducing disease and contributing to an overall higher standard of public health. Disease-causing organisms can be substantially reduced or even eliminated from the water supply by disinfection with chlorine or other methods.

A relatively recent development in water treatment is the threat from ingestion of certain categories of waterborne pathogens, specifically protozoa and enteric viruses, which are resistant to traditional water-disinfection practices. The situation is complicated further by ineffective methods for measuring their presence in water. The use of coliform indicator bacteria as a surrogate for assessing the safety of water supplies was adopted with the initial bacteriological standards in 1914. These tests, however, are ineffective as indicators of the presence or absence of protozoans, such as *Cryptosporidium* and *Giardia*, which produce resistant, long-lived cysts and have different life-cycles and environmental-transport mechanisms from bacteria. Pathogenic protozoans must be specifically identified instead of being cultured or grown like most surrogate or fecal indicators. Likewise, waterborne viruses are not well predicted by traditional indicator bacteria, and the current methods for measuring total-recoverable viruses are recognized as being difficult to implement. Improved methods are needed to detect these pathogens in water.

Toxic and Hazardous Substances.—Recent decades have brought increasing concerns for potential adverse human and ecological health effects resulting from the production, use, and disposal of numerous chemicals that offer improvements in industry, agriculture, medical treatment, and even common household conveniences. Research has shown that many such compounds can enter streams and ground water, disperse, and persist to a greater extent than first anticipated. Pharmaceuticals, and other consumables, as well as biogenic hormones, are released directly to the environment after passing through

Table 4. *Land-surface subsidence in selected areas in the Southwest.*

[Data from Leake, 1987]

Arizona		California		Nevada		New Mexico		Texas	
Location	Feet	Location	Feet	Location	Feet	Location	Feet	Location	Feet
Eloy	15	Lancaster	6	Las Vegas	6	Albuquerque	1	El Paso	1
West Phoenix	18	Southwest of Mendota	29			Mimbres Basin	2	Houston	9
Tucson	<1	Davis	4						
		Santa Clara Valley	12						

wastewater-treatment processes (in wastewater-treatment plants or domestic septic systems), which often are not designed to remove them from the waste stream. These chemicals are entering the subsurface through septic leachfields and by the growing popularity of applying treated municipal effluent to the land surface as a water-conservation practice (Cordy and others, 2004). The animal production industry is a heavy user of pharmaceutical products and growth hormones, and the standard practice for animal-waste disposal also is land application. Until recently, there have been few analytical methods capable of detecting most of the target compounds at low concentrations that might be expected in the environment (Sedlak and others, 2000). In a recent national reconnaissance of pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, Kolpin and others (2002) detected compounds of a wide range of residential, industrial, and agricultural origins (fig. 34). Steroids, nonprescription drugs, and an insect repellent were the three chemical groups most commonly detected in susceptible streams. Detergent metabolites, steroids, and plasticizers generally were found at the highest concentrations of any of the contaminants.

The transport and ultimate fate in the environment of many toxic and hazardous substances including synthetic organic chemicals after their intended use are not well known. Science is just now beginning to monitor low concentrations (microgram to nanograms per liter) of pharmaceuticals, hormones, and other synthetic organic contaminants at the low levels required to track their occurrence in streams, reservoirs, and ground water. An improved understanding of the occurrence, fate, and transport of these contaminants is needed, as well as a knowledge of the potential effects of these chemicals on plant, animal, and human reproduction and development. Some of these chemicals may contribute to deformities in frogs and other amphibians, altered sexual orientation and maturation of fish, and result in other undesirable effects throughout the food chain, such as bioaccumulation of contaminants in birds of prey (Daughton and Ternes, 1999). The growing practice of recharging treated effluent that contains organic-wastewater contaminants will require scientific information about these compounds, particularly pharmaceuticals and personal care products that are designed to stimulate a physiological response in humans, plants, and animals.

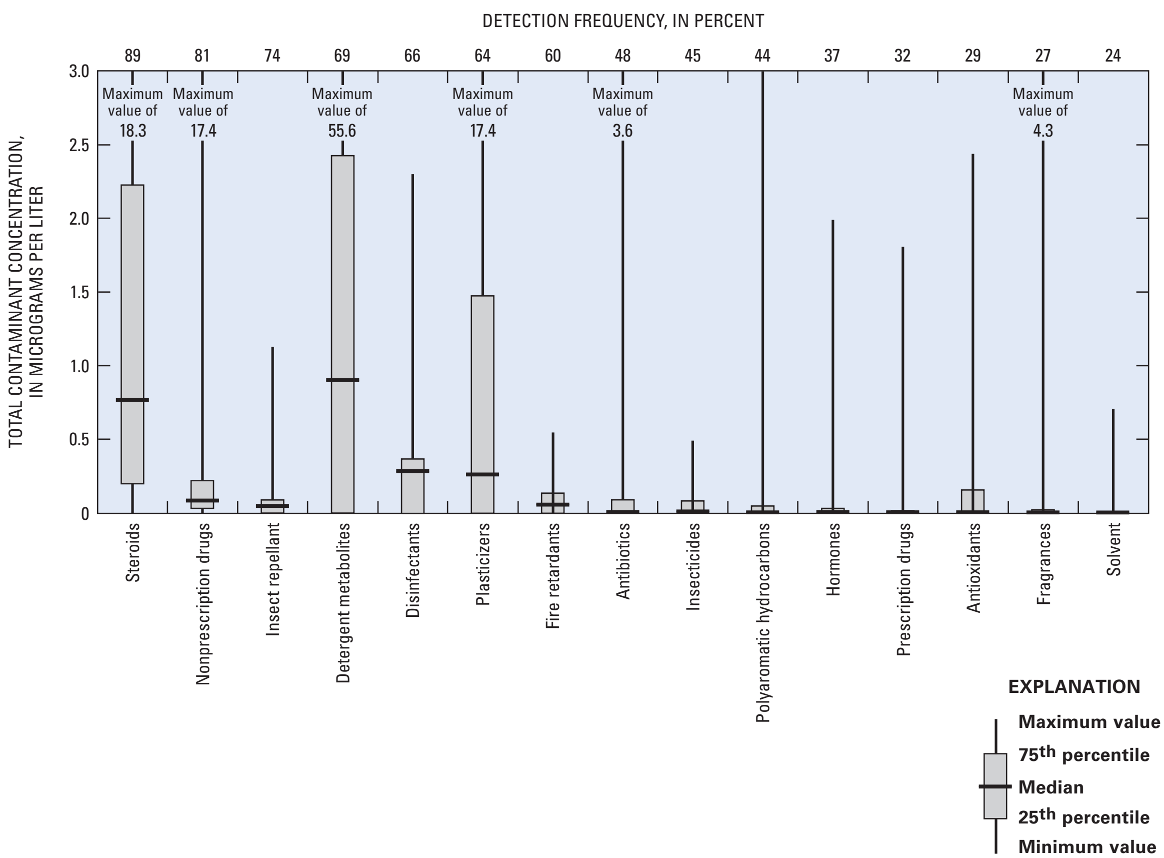


***Figure 34.** Concentrations and detection frequency of organic wastewater contaminants in U.S. streams. From Buxton and Kolpin (2002).*

***"...meeting the needs of the present without compromising the ability of future generations to meet their(s)."*—Gro Brundtland, Former Norwegian Prime Minister**

Sustainability Phase

Water managers in the Western United States are increasingly seeking strategies to achieve a level of water use that can be sustained long term. Sustainability, as presently interpreted, goes beyond mere water availability for human water supply and includes water for ecosystems and even individual species. In the most widely accepted definition, Gro Brundtland, Former Norwegian Prime Minister, has defined sustainability as "…meeting the needs of the present without compromising the ability of future generations to meet their(s)."

Surface water, because it is renewable, and water stored in reservoirs, because it can be managed across multiple years, are important components of any sustainable water-supply strategy. For example, Reclamation manages 348 reservoirs in 17 Western States that can store a total of 256 million acre-feet of water. The value of this storage becomes most evident during periods of drought. At the beginning of the 21st century, many areas of the West were experiencing the driest year (2002) in the last 100 years, and although reservoirs are low (fig. 12) and being depleted, the current Western drought has been somewhat ameliorated by this large volume of reservoir storage.

"With drought conditions in most of the West persisting, we are at a critical juncture, only by employing the same foresight, planning, and cooperation as early Western settlers will we be able to ensure adequate water for our cities and farms, recreation, fish and wildlife, hydropower, and many other uses."
—Bureau of Reclamation, Commissioner Keys, March 2003

Sustainability by this definition is superficially appealing, but is and will continue to be a significant challenge for science to translate into measurable water-management strategies. A sustainable water supply for a community ideally would provide enough water to support population and economic growth and be sufficient to endure protracted periods of drought. Strategies of ground-water use to address sustainability are presented and examined by Alley and others (1999) and Galloway and others (2003). In order to sustain valued ecosystems and endangered species, segments of our society expect water to be made available, in volumes not easily quantified, to meet key habitat requirements.

The water-management strategies being used to achieve sustainability require more complex and sophisticated scientific information than in the past phases of water development. In the case of sustaining ecosystems and endangered species, new demands will be placed on science and scientists. Genuine integrated science will be required to better quantify and monitor changes in the hydrologic system, physical habitat requirements of riparian ecosystems, and life-sustaining needs of individual species. In this environment, scientific investigations need to be responsive to management questions and germane to the issue. In reality, water-supply and ecosystems needs may be mutually exclusive in places. Science can play an important role in defining the consequences and tradeoffs.

Determination of Sustainable Ground-Water Use

The sustained use of ground water involves a search for a rate of withdrawal that is considered renewable—a level of use free of current and future adverse effects. The determination of sustainable use of ground water is not solely a scientific determination but rather involves complex interactive decisions that involve society's values, environmental consequences, and economic concerns (Alley and Leake, 2004). There is a commonly held, inaccurate belief in the West, when estimating water availability and developing sustainable water-supply strategies, that ground-water use can be sustained if the amount of water removed is equal to recharge—often referred to as "safe yield." In order to examine this strategy more carefully, an analogy is made comparing an aquifer and a reservoir behind a dam on a river (fig. 35). If withdrawals from a reservoir equal inflows, the river below the dam will be dry unless the water level in the lake is allowed to fall. The same principle can be applied to a ground-water reservoir, if pumping (discharge) equals inflows (recharge), the outflows (subsurface flow or discharge to springs, streams, or wetlands) from the aquifer will decrease to zero, resulting in some adverse consequence at some point in time. The effects of reducing or eliminating outflows from an aquifer are usually outside the scope of human observation, either in the subsurface or over long time scales. There are occasions, however, when effects have been observed, such as declining lake levels. The distinction between safe yield and sustainable yield is discussed in further detail by Alley and Leake (2004).

This strategy of pumping a volume of water equal to recharge implies that a predevelopment water budget for a ground-water system (that is, a water budget for the natural conditions before anthropogenic disturbances) can be used to calculate the volume of water available for consumption (or the safe yield). This concept has been referred to as the "Water-Budget Myth" (Bredehoeft and others, 1982). It is a myth because it is an oversimplification of the information needed to understand the effects of developing a ground-water system. As human activities change the system, the components of the water budget (inflows, outflows, and changes in storage) also change and should be accounted for in any management decision (Alley and others, 1999).

> ***"A simple 100-year race to the bottom [of an aquifer] is not a good management rule"***
> **—David Harrison, Colorado, Attorney at Law**

The implications of long-term droughts also are considered in long-term water-management strategies. Droughts, resulting in reduced ground-water recharge, may be viewed as a natural stress on a ground-water system that, in many ways, has effects similar to ground-water withdrawals—namely, reductions in ground-water storage and accompanying reductions in ground-water discharge to streams and other surface-water bodies. At the same time, the Nation's aquifers provide a huge volume of water storage compared to constructed surface-water storage. These large underground storage reservoirs can function effectively as a buffer against the annual to decadal variability of climate. Despite this buffering capacity against even annual declines in precipitation, the stress on some aquifers can be increased immediately if pumping increases. Effective recharge to aquifers, however, may occur only as the result of infrequent climatic conditions (El Niño) or hydrologic events rather than a simple percentage of annual precipitation. Water availability from storage in an aquifer, therefore, may not be substantially reduced despite a drought-induced short-term deficit. Reductions in storage, however, can have adverse consequences—lowered ground-water levels may cause aquifer-system compaction and land subsidence and may induce poorer quality water from deep in the aquifer system to flow to water-supply wells.

Arguably, there is no volume of ground-water use that can be truly free of any adverse consequence, especially when time is considered. The direct hydrologic effects will be equal to the volume of water removed, but those effects may require decades to centuries to be manifest. Because aquifer recharge and ground-water withdrawals can vary substantially over time, these changing rates can be critical information for improving management strategies. The dependence of many communities in the West on ground water in storage is a management strategy that is not sustainable for future generations. Prudent management would give serious consideration to strategies that rely on surface water and hold ground water in reserve. Because of the ability to buffer short-term fluctuations in supply, ground water will undoubtedly be an integral part of sustainable-use strategies. Large-scale withdrawals from ground-water storage can be used in times of crisis or episodic shortage

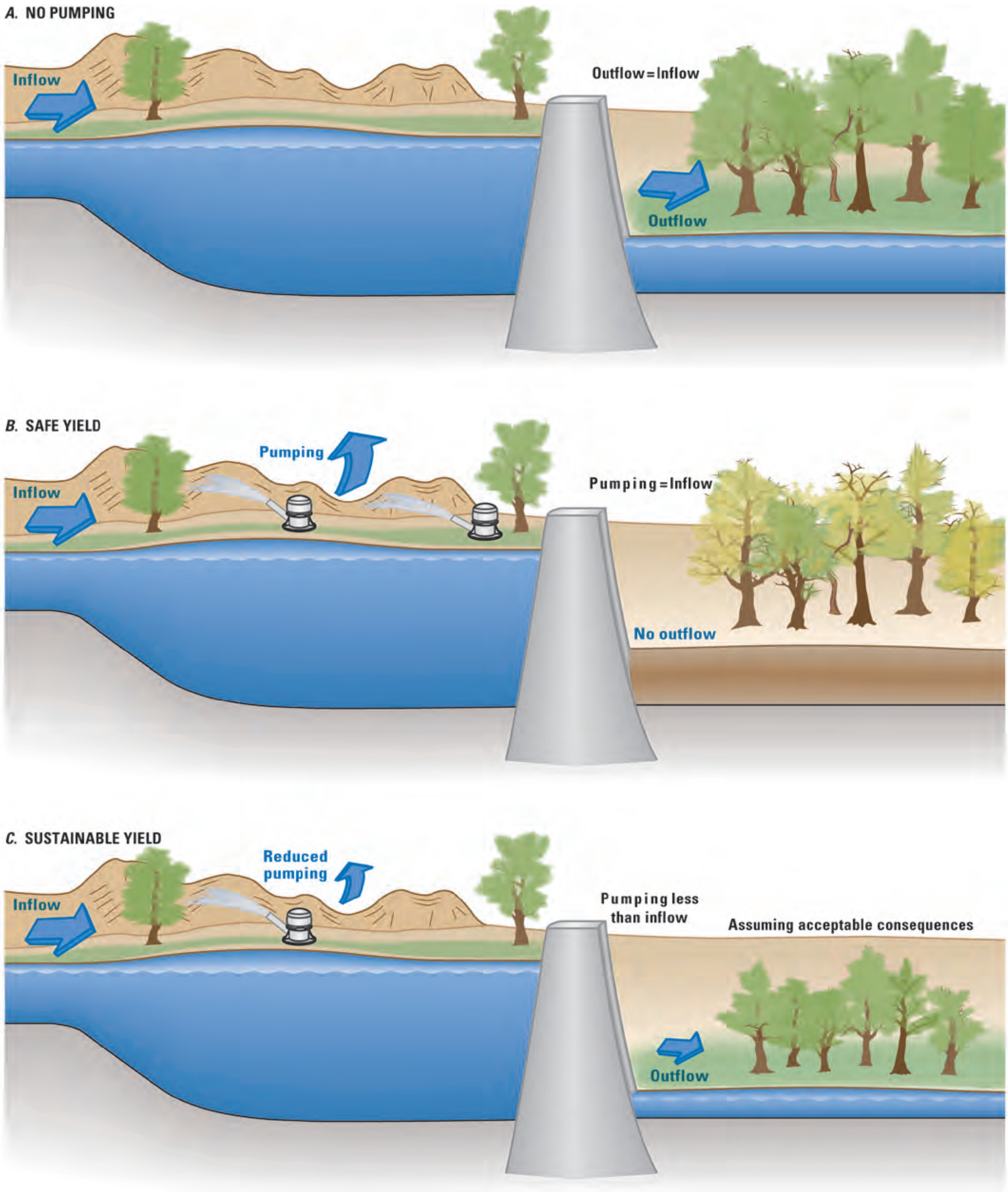


Figure 35. *Illustration of sustainable pumping from a ground-water aquifer by comparison to surface-water reservoir. Sustainable yield can be achieved by accepting some consequences of pumping. Safe yield often is referred to as pumping equal to recharge, but as shown, can result in no outflow and unacceptable consequences.*

to achieve sustainability, and likewise during periods of overabundance, water can be stored or banked in aquifers. For more information on strategies for sustaining ground-water availability, the reader is referred to Alley and others (1998), Winter and others (1998), Taylor and Alley (2001), and Galloway and others (2003).

Scientific Information

Scientific information is useful in the determination of a sustainable level of ground-water use of an aquifer system. The gathering of scientific information is guided by the terms of the hydrologic budget described in the section entitled, "Ground Water." Although an estimate of all terms is required, the most difficult term to accurately estimate over time is recharge—a challenge for science. Recharge to an aquifer system cannot be measured directly because it occurs in a disseminated manner in space and time. Water withdrawals and the change in aquifer storage can be measured and are the important budget terms that can be altered by human use. Recharge can be determined as the residual term of the water budget. Additional details on the types and amounts of scientific information helpful in defining a sustainable use of ground water are presented in table 5.

Ground-water-level monitoring in the United States, despite its importance, is fragmented and typically associated with local water-supply projects. Consequently, a stable base network of water-level monitoring wells exists only in some locations. For many decades, periodic calls have been made for a nationwide program to obtain more systematic and comprehensive records of water levels in observation wells as a joint effort by the USGS in cooperation with the States and local agencies. The National Research Council (2000) recently stated, "An unmet need is a national effort to track water levels over time in order to monitor water-level declines." Similarly, the H. John Heinz III Center (2002) stated that data on ground-water levels, potential changes, and rates of change are "not adequate for national reporting." The principal types of scientific information to support ground-water sustainability were stated by Alley and others (1999) and are presented in table 5. Basic water-data-collection programs should build upon the existing networks of streamflow-gaging stations (see Box D on National Streamflow Information Program) and ground-water-level monitoring sites, expanded to include aquifer-storage change monitoring and the quantification of recharge and discharge.

> ***"An unmet need is a national effort to track water levels over time in order to monitor water-level declines"***
> **—The National Research Council, 2000**

Much as debits, credits, and savings in a financial budget need to be quantified to maintain fiscal responsibility, the Nation's water use needs to be quantified within the water-budget context to ensure adequate availability of water as future water demands regionally fluctuate because of changes in climate, urban growth patterns, agricultural practices, and energy needs (National Research Council, 2002).

Ground-water flow models are useful to estimate future effects of pumpage. Models also can be used to adjust and estimate unmeasured terms in the budget. The intention of this discussion is not to prepare a study plan with sufficient detail as to be implemented, but rather to discuss in broad terms the types of information necessary. The challenge for science is to inform water managers and the public of these consequences, so that if the supplies are nonrenewable, at least the consequences and the risks are known to the stakeholders.

National Streamflow Information Program

Information on the quantity and timing of the streamflow in the Nation's rivers is a vital asset that safeguards lives and property and helps to ensure adequate water resources for a healthy environment and economy. The USGS operates and maintains approximately 7,000 streamflow-gaging stations, which provide long-term, accurate, and unbiased information that meets the needs of many diverse users. In 1998, Congress expressed concern about the health of the USGS streamflow-gaging program with the following observation:

> *"The Committee has noted the steady decline of streamflow-gaging stations in the past decade, while the need for streamflow data for flood forecasting and long-term water management uses continues to grow."*

In response, the USGS designed the National Streamflow Information Program (NSIP), which consists of five components:

1. An improved network of streamflow-gaging stations;
2. Collection of critical information during floods and droughts;
3. Periodic assessments and evaluation of streamflow characteristics to assess the impacts of climate and land-use change;
4. A highly reliable system for delivering data to users;
5. A program of research and development for building better data collection, delivery, and interpretation capabilities for the future.

The USGS National Streamgaging Network consists of a core of USGS-funded and -operated streamflow-gaging stations, gaging stations operated by the USGS but funded in cooperation with other agencies, and gaging stations funded and operated by other agencies that provide data appropriate to meet NSIP goals. Although the National Streamgaging Network is operated primarily by the USGS, it is funded by a partnership of 800 agencies at the Federal, State, tribal, and local levels.

Streamflow-gaging station on the East Verde River in central Arizona. Photograph provided by the U.S. Geological Survey.

The USGS-NSIP will provide a "backbone" or core of gaging stations that are of such critical importance to the National Streamgaging Network that their operation must be ensured. NSIP was created in response to Congressional and stakeholder concerns about (1) a loss of gaging stations, (2) a disproportionate loss of gaging stations with a long period of record, (3) the inability of the USGS to continue operating high-priority gaging stations when partners discontinue funding, and (4) the increasing demand for streamflow information due to new resource-management issues and new data-delivery capabilities.

For more information about the NSIP program, visit *http://water.usgs.gov/nsip*

Table 5. *Principal types of monitoring and research needed to analyze water supply and ecosystem function.*

Activity	Scientific information	
	Monitoring	Research and investigations
• **Determination of sustainable ground-water use**		
	◦ Precipitation, evaporation, and water-use data; characteristics of streamflow into the basin; topographic maps showing the stream-drainage network, watershed boundaries, surface-water bodies, landforms, and locations of structures and activities related to water; geologic maps of surficial deposits and bedrock; maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normal seasonal flow.	Resource availability, quality, and use; flow duration; pre- and post-impoundment studies.
	◦ Aquifer characteristics, including water levels; saturated-thickness maps of unconfined (water-table) and confined aquifers; maps of tops and bottoms of aquifers and confining units; estimates of specific yield, storativity, and transmissivity; maps of ground-water flow direction; storage change; environmental tracers and other chemical substances and isotopic compositions.	Resource availability, quality and use studies; geologic maps; aquifer-property map.
• **Artificial recharge**		
	◦ Geochemical characteristics of earth materials, naturally occurring ground water in aquifers and confining units and the artificially recharged water; spatial distribution of water quality in aquifers, both areally and with depth; location of recharge areas (areal recharge from precipitation, losing streams, irrigated areas, recharge basins, and recharge wells), and estimates of recharge; maps showing variations in storage coefficient for aquifers; average hydraulic conductivity maps for aquifers and confining units and transmissivity maps for aquifers; hydrogeologic maps showing extent and boundaries of aquifers and confining units (three-dimensional framework), sediment, and basic water-quality data. A monitoring program to sample wells for water quality and pathogen characteristics. Streamflow data, including measurements of gain and loss of streamflow between gaging stations; chemical characteristics of artificially introduced waters or waste liquids; temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers.	Analytical methods for pathogen detection, long-term prediction of geochemical changes in aquifer.
• **Conservation, conjunctive use, water reuse, and desalination**		
	◦ Water-use patterns as feedback; geochemical conditions and presence of pathogenic organisms; sources and types of potential contaminants; measurements of surface-water diversions and return flows; spring discharge.	Research and development for improved technology for all water strategies.
• **Sustaining valued ecosystems**		
	◦ H. John Heinz III Center key indicators such as size of riparian areas and wetlands, determination of water requirements of riparian vegetation, ground-water levels below valued ecosystems and trends.	
• **Sustaining individual endangered species**		
	◦ Population time-series data for individual species; age classes; recruitment rates. Physical-habitat requirements, such as water levels; instream flow rates; water temperature and chemical quality; food sources; streamflow quality (water-quality sampling in space and time), particularly during periods of low flow; sources and types of potential contaminants; history and spatial distribution of pumping rates in aquifers; quantities and locations of interbasin diversions; estimates of total ground-water discharge to streams; estimates of ground-water age at selected locations in aquifers.	Understanding flow and habitat requirements of aquatic communities; long-term prediction and change studies.

CASE EXAMPLE—*Middle Rio Grande Basin, New Mexico*

The citizens of Albuquerque, New Mexico, are dependent upon ground water from the Santa Fe Group aquifer system. The Middle Rio Grande Basin (fig. 36), through which the Rio Grande flows, was home to about 690,000 people in 2000, or about 38 percent of the population of New Mexico (Bartolino and Cole, 2002). The Southwest's moderate climate, expanding employment opportunities, and abundant recreation activities have stimulated immigration and population growth. These Southwestern desert environments contain fragile landscapes and finite water resources that limit growth. Water is a critical factor required for continued growth and prosperity in the Albuquerque area. The New Mexico Office of the State Engineer (NMOSE) considers surface flow of the Rio Grande to be fully appropriated to meet the needs of irrigation agriculture, Indian tribal lands, and required water deliveries to Texas and Mexico. Most residential, industrial, and municipal water needs in the basin today are met by extraction of ground water. The USGS and partner agencies are studying the Middle Rio Grande Basin to improve knowledge and understanding of the hydrology, geology, landforms, and land-use characteristics of this region of central New Mexico (Bartolino and others, 2002). The USGS studies have explored hydrogeological conditions in the urban areas where ground-water withdrawals are currently occurring and have used diverse methods to infer these conditions elsewhere in the basin where future ground-water development could occur. There are four main goals of these long-term multidisciplinary studies:

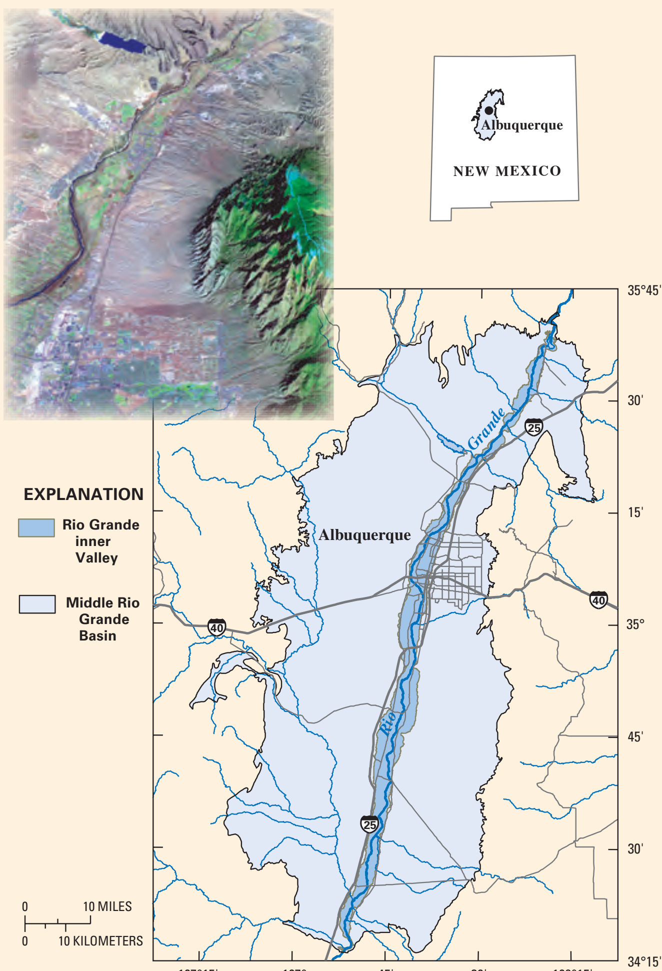


***Figure 36.** Location of the Middle Rio Grande Basin and the city of Albuquerque, New Mexico. Low-oblique image of the Albuquerque metropolitan area (image provided by Stan Wilds, U.S. Geological Survey).*

1. To study the hydrology, geology, and land-surface characteristics of the basin to provide the scientific information useful for water-resources management.

2. To increase the understanding of the aquifer system and to extend the knowledge of geology and land-surface characteristics into the northern and southern reaches of the basin.

3. To improve the understanding of the water resources of the basin. This understanding then will provide the information needed by managers to plan and develop water supplies for the population of the Middle Rio Grande Basin.

4. To determine to what extent the Rio Grande and the Santa Fe Group aquifer are hydrologically connected.

Scientific Information Collected and Findings.—The scientific investigations of the Middle Rio Grande Basin have resulted in the collection of a wide variety of data and information by scientists from different agencies. The information presented in this section is provided not as a prescription for every ground-water sustainability issue, but as an example of the types of scientific information that were useful for the Middle Rio Grande Basin. For more detail about the geohydrology of the Middle Rio Grande Basin, the reader is referred to Bartolino and others (2002).

- Environmental tracers and chemical constituents were analyzed in water samples collected from 275 wells in the basin to determine the age of ground water, to define zones of differing water quality, and to locate areas of recent recharge.

This sampling has made the basin one of the most intensively sampled basins in the world for environmental tracers. Among the tracers used were hydrogen, helium, oxygen, carbon, and sulfur isotopes; dissolved gasses; chlorofluorocarbons; and sulfur hexafluoride. This analysis has determined that water along the western edge of the basin is about 20,000 years old, and water in other areas, such as in the inner valley of the Rio Grande and along some arroyos and mountain-front areas, has been recharged in the past 50 years. These ground-water ages also have provided calibration data for ground-water flow models of the basin (Plummer and others, 2001).

- Early in the study, nonlinear regression methods were applied to a ground-water-flow model of the basin to evaluate various hypotheses about the hydrogeologic framework of the basin. The resulting information was used to refine the understanding of the hydrology of the basin. In addition, the resulting model served as a basis for a NMOSE management model of the basin (Tiedeman and others, 1998; Barroll, 2001).
- Geophysical methods were used to interpret different properties of the aquifer system. Gravity techniques were used to estimate the total thickness of the Santa Fe Group deposits, which are less dense than the underlying and surrounding bedrock. High-resolution aeromagnetic surveys delineated faults that offset water-bearing units in the aquifer system and showed the extent of buried igneous rocks, which have different hydraulic properties than the surrounding sedimentary deposits. Airborne time-domain electromagnetic surveys were used to determine variations in the electrical resistivity of the Santa Fe Group that are related to variations in grain size and hydraulic properties (Grauch and others, 2002).
- Because of the limited usefulness of ground-water levels measured in or near production wells, the USGS, in cooperation with the city of Albuquerque, NMOSE, and Bernalillo County, New Mexico, began a program in 1996 to install specialized observation wells in the Middle Rio Grande Basin. Most of these wells are in groups, or nests, of three or more wells completed at different depths in the aquifer. In 2002, there were 59 such monitoring wells installed at 23 sites. Continuous water-level recorders have been installed on nearly all these wells, and all wells have been incorporated into the city of Albuquerque ground-water-level monitoring program.
- To estimate the degree of ground- and surface-water interaction between the Rio Grande and the Santa Fe Group aquifer system, a variety of techniques were applied, including analyses of the distribution of water temperature, electromagnetic surveys, and streamflow losses. These techniques have supplied estimates of the direction and rate or flux of water moving between the river and aquifer system at selected sites (Bartolino, 2002).
- Three methods are being used to check for the onset of land subsidence related to ground-water withdrawals: (1) a high-precision survey network in the Albuquerque area, (2) an extensometer in northern Albuquerque, and (3) Interferometric Synthetic Aperture Radar (InSAR) analysis (fig. 37). The first two methods have not detected land subsidence greater than the detection threshold of 0.5 inch (12.7 millimeters). InSAR analysis, however, in conjunction with water-level data, shows reversible and possibly permanent land subsidence from aquifer-system deformation in parts of the Middle Rio Grande Basin (Heywood, Bartolino, and Galloway, 2002).
- The conceptual geologic framework of the Middle Rio Grande Basin was revised and updated by mapping the surficial deposits and bedrock outcrops of the Middle Rio Grande Basin and adjoining areas. Several new maps (1:24,000 scale) are now available online in digital form at URL *http://geoinfo.nmt.edu/statemap/quads/index/home.html* (Bauer, 2001).
- An urban-growth model was used to project the extent of the urbanized Albuquerque area in 2050 to help city managers form sound policies for guiding sustainable growth. Because the availability of water may ultimately be limited, decisions on growth can be improved by realistic and scientific projections of growth patterns and changes (Hester and Feller, 2002).
- Research on mountain-front recharge involved a variety of techniques, including water-temperature methods, steady-state centrifuge analysis of cores, chloride-mass balance methods, and geochemical analysis of core samples and pore water. These studies have helped confirm that there is substantially less ground-water recharge along mountain fronts in the Middle Rio Grande Basin than previously estimated (Bartolino and Constantz, 2002).

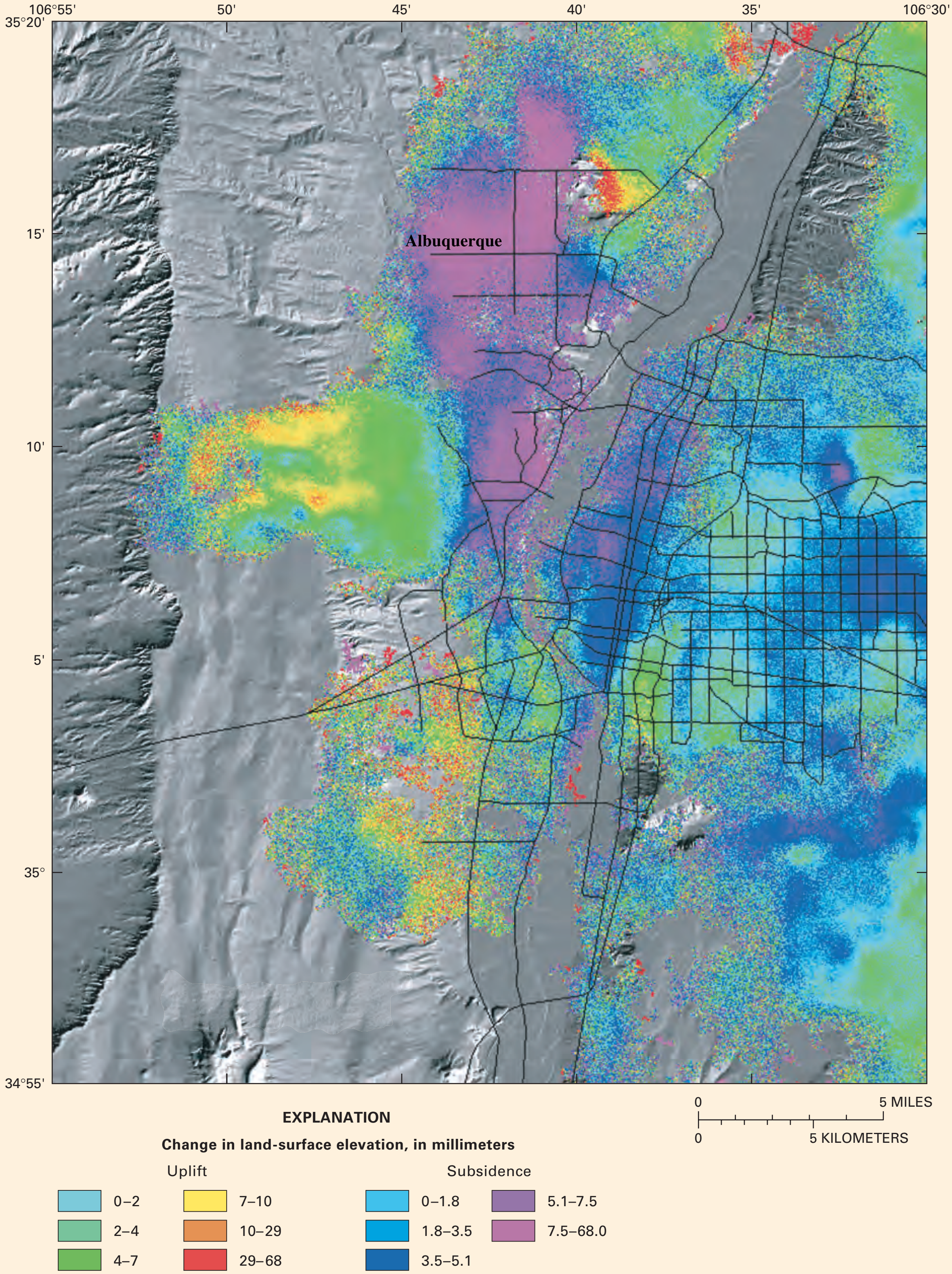
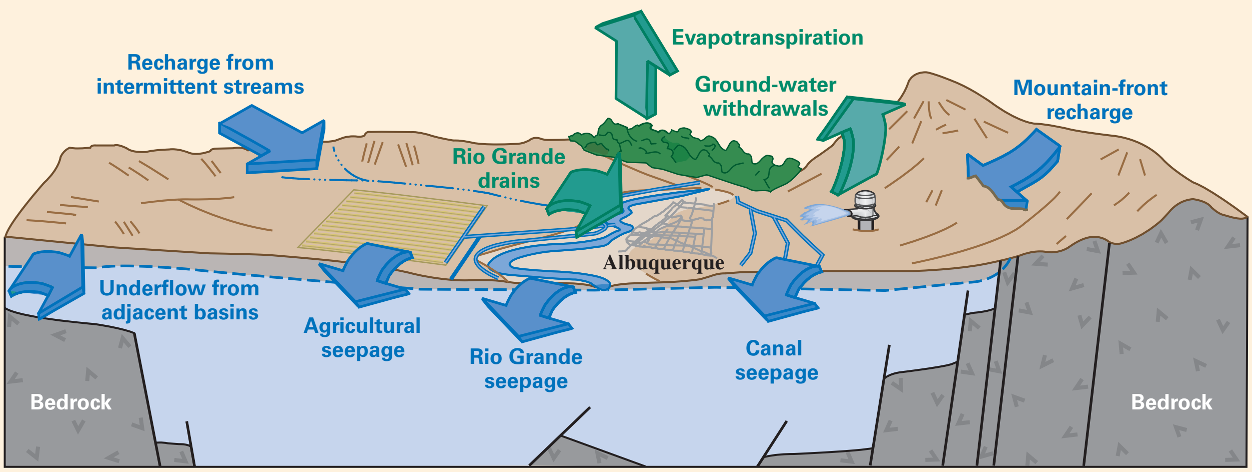


Figure 37. *Interferogram showing ground displacement in Albuquerque, New Mexico, from July 2, 1993, to April 1, 1996. Modified from Heywood, Galloway, and Stork, 2002.*

These data-collection efforts and scientific investigations resulted in many important findings that can aid in the water-resources management of the basin. A few of the key findings are presented here; more detail is available from Bartolino and Cole (2002).

- The water resources of the Middle Rio Grande Basin are a combination of surface-water and ground-water systems that are closely connected. The ground-water budget constructed from the information collected, shows that water withdrawals exceed recharge (or depletion of storage) by about 60,000 acre-feet per year (fig. 38).
- When ground water is pumped from an aquifer system faster than it is recharged for a prolonged period of time, ground-water levels decline, and the process is referred to as ground-water mining. Water-levels have declined more than 160 feet in an area beneath the eastern part of Albuquerque.
- Previous studies found the Rio Grande to be well connected hydraulically to the Santa Fe Group aquifer system, and years of water-management policy were based on this understanding. Recent studies of the interaction between the river and aquifer (including ground-water-flow simulations) indicate that the hydraulic connection is less than previously thought.
- As Albuquerque grew, most of the new municipal-supply wells were completed in highly productive parts of the Santa Fe Group aquifer system. Areas of high-quality water within the Middle Rio Grande Basin are relatively small, and much less water is available for pumping than previously thought.
- Estimates of mountain-front recharge to the Santa Fe Group aquifer system using direct measurements and ground-water dating show that recharge is substantially less than previously believed.



Simulated annual water budget for a ground-water-flow model (2002)—Values are in acre-feet per year

WATER INFLOW	
—Mountain-front recharge	12,000
—Recharge from intermittent streams	9,000
—Underflow from adjacent basins	31,000
—Canal seepage	90,000
—Agricultural seepage from on-farm irrigation	35,000
—Rio Grande main stem and Cochiti Lake seepage	316,000
—Jemez River and Reservoir seepage	17,000
—Septic-tank return flows	4,000
—Aquifer storage (net storage depletion)	**60,000**
Total	574,000

WATER OUTFLOW	
—Rio Grande riverside drains	–208,000
—Rio Grande interior drains	–134,000
—Ground-water withdrawals	–150,000
—Riparian and wetland evapotranspiration	–84,000
Total	–575,000

Figure 38. *Water budget of the Middle Rio Grande Basin, New Mexico. From McAda and Barroll (2002).*

Long-Term Artificial Recharge

Artificial recharge of aquifers is a familiar concept in the water industry, and experimentation dates back to the 1930s (Weeks, 2002). One definition of artificial recharge is "the practice of increasing by artificial means the amount of water that enters a ground-water reservoir" (Todd, 1959). Today, artificial recharge is rapidly gaining acceptance as a conjunctive water-use strategy and as a mitigation measure for ground-water overdraft. Aquifer storage and recovery (ASR) is a simple concept whereby treated wastewater effluent, imported surface water, excess streamflow, or stormwater runoff is used to recharge an aquifer for subsequent withdrawal. Two principal methods of ASR are used—a high-rate method, whereby recharge water is directly injected into an underground source of drinking water using recharge wells (Class V injection wells as defined by the U.S. Environmental Protection Agency under the Underground Injection Control Program), and a low-rate method, whereby the recharge water is diverted to recharge basins and allowed to slowly percolate into the underlying shallow aquifer (fig. 39). Artificial recharge also is being used to control the migration of seawater into coastal aquifers being extensively pumped for water supply. For example, in Orange County, California, freshwater is injected into this coastal ground-water basin to arrest the intrustion of saltwater (fig. 40).

Arizona is rapidly expanding its capability to recharge aquifers with Central Arizona Project (CAP) water. There are about 66 active or permitted sites in Arizona where about 500,000 acre-feet of water per year is recharged, for a cumulative total through 1999 of about 2.4 million acre-feet (fig. 41). Arizona and Nevada have reached a novel agreement to "bank" Colorado River water in alluvial basins. Part of Nevada's allocation of river water will be stored in Arizona basins to be withdrawn later in a complicated exchange for future flows from the river. This ASR method of water management is relatively inexpensive in comparison to the construction and operation of new reservoirs and can potentially accommodate a much greater volume of water with much less water lost due to evaporation.

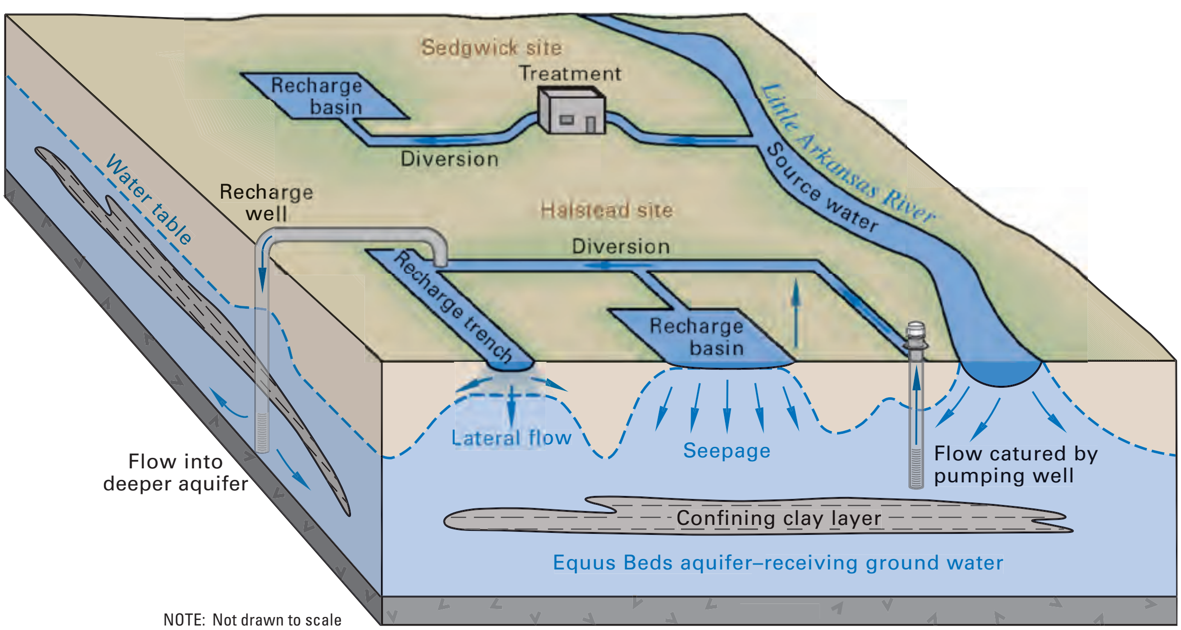


***Figure 39.** Artificial-recharge processes as actively used near Wichita, Kansas.*

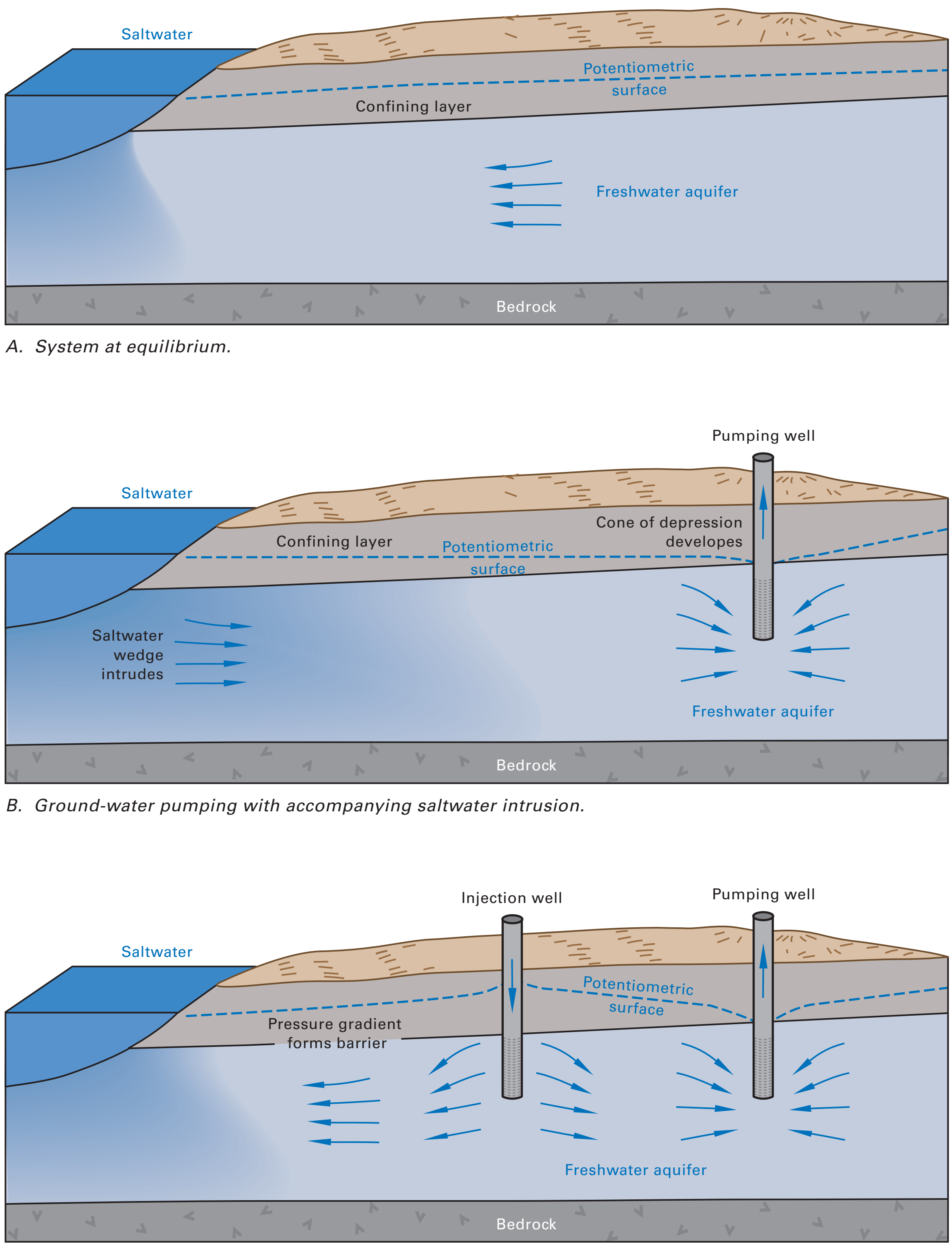


Figure 40. *Artificial recharge used to provide a barrier to saltwater intrusion in the Los Angeles, California, area. A, Under natural conditions, discharge from the freshwater aquifer restricts saltwater. B, A cone of depression develops from ground-water pumping and induces saltwater intrusion. C, The onset of injected water changes the equilibrium. A pressure gradient forms a barrier to seawater intrusion. Modified from Edward and Evans (2002).*

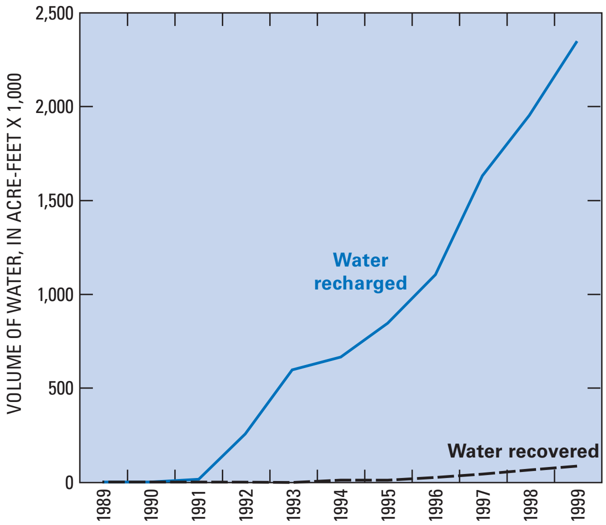


Figure 41. *Cumulative volume of water artificially recharged in Arizona, 1989–1999. (Source: Arizona Department of Water Resources.)*

Scientific Information

Artificial recharge, as a long-term water-management strategy, requires specialized hydrogeologic information on the water to be recharged and on the aquifer properties and conditions. For all its promise, artificial recharge has not been in operational practice long enough to understand the full consequences of this practice in many places. Scientific uncertainties span a variety of disciplines, including hydrogeology, geochemistry, and microbiology. The challenge for science will be to determine the long-term geochemical equilibrium of recharging nonnative water having certain dissolved constituents into the aquifer. This process may cause precipitation reactions that reduce aquifer permeability. The host aquifer may contain native water that is brackish or has constituent concentration that requires treatment to achieve potable standards. The aquifer being recharged in all cases would be classified as an underground source of drinking water under the Safe Drinking Water Act. The water to be recharged, either treated wastewater effluent, stormwater runoff, streamflow, or deep-aquifer water, should essentially be uncontaminated—free from trace elements, pesticides, organic compounds, pharmaceuticals, and pathogens. A further complication is that water purveyors may not be able to recover recharge water within their jurisdiction if aquifer conditions favor rapid flow out of the area. Ground-water models are useful for estimating ground-water flow rates and directions and responses to pumping stress. More detail on the types of scientific information useful to support artificial recharge is presented in table 5.

Regulations are being proposed in some States to ensure that adequate soil-retention time requirements are met for pathogen removal from recharged waters. As a result, there is a need for predicting the degree of pathogen attenuation in the subsurface to protect ground-water resources. The current knowledge about attenuation as reclaimed water moves through the subsurface has largely been derived from mathematical models and laboratory studies. Extension of pathogen-attenuation studies to the field scale is now needed.

Some of the scientific information useful to support aquifer recharge is as follows:

- Regional ground-water assessments that provide a geologic and hydrologic framework for developing recharge applications;
- Processes controlling changes in aquifer permeability (dissolution, bio-fouling, trapped gasses);
- Multitracer and geophysical approaches to determine short- and long-term efficiencies of recharge/withdrawal cycles;
- Long-term fate and transport of introduced contaminants, such as pathogens, pharmaceuticals, and disinfection by-products;
- Mobilization of trace elements;
- Simulation of variable-density flow and transport; and
- Role of dissolved organic matter in changing aqueous and solid-phase geochemistry.

Artificial recharge is extensively practiced in the Greater Los Angeles, California, area where ground water provides about one-third of the water supply. Two separate programs of artificial recharge are used in this area, but they are designed to achieve different objectives. Water is injected into aquifers along the coast to control saltwater intrusion, and water is spread into percolation ponds to replenish the ground water.

The encroachment of saltwater from the Pacific Ocean has resulted from ground-water pumping that has gradually lowered the water table in the freshwater aquifer until it is below sea level. To prevent further saltwater intrusion and to replenish the ground-water supply in the West Coast Basin of Los Angeles County, the Los Angeles Department of Public Works operates the West Coast hydraulic barrier project composed of more than 200 wells that inject freshwater into the aquifer (fig. 42). The injection water is a blended combination of imported water and recycled, highly treated (beyond tertiary) effluent. Advanced-treatment processes of reverse osmosis and activated carbon adsorption are used on the recycled product to meet drinking-water standards. Scientific investigations are determining the main pathways for seawater intrusion and the efficacy of the hydraulic barrier system.

Recycled wastewater effluent, imported water, and local runoff are recharged in the Montebello Forebay area of Los Angeles County (fig. 42) using spreading ponds and injection wells to augment water supplies. The Montebello Forebay is an area of the basin where the underlying sediment is relatively coarse, which allows surface water to infiltrate the sediment and recharge the ground-water system. Water managers are interested in knowing where the recharged water goes in the subsurface. They also need to know the percentage of recycled wastewater that is being pumped from production wells downgradient from the spreading ponds of Montebello Forebay (fig. 43; Schroeder and Anders, 2002). The USGS is working in cooperation with several local agencies to better understand the transport and fate of water diverted into spreading ponds in the Montebello Forebay.

Scientific Information Collected.—Scientific information is collected by many agencies in the Los Angeles area, including the Water Replenishment District of Southern California, the Los Angeles County Department of Public Works, the West Basin Municipal Water District, and local municipalities and investigators.

The USGS has installed more than 30 multiple-well monitoring sites throughout the Los Angeles Basin to better understand the physical and chemical properties of the aquifer being recharged. Chemical, geologic, hydrologic,

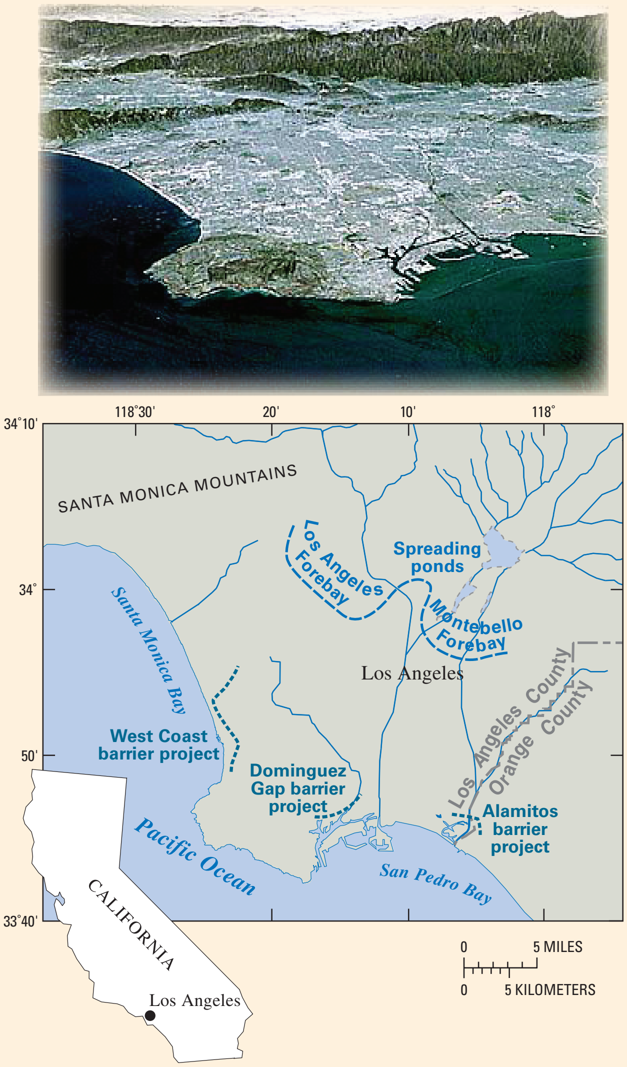


Figure 42. *Artificial-recharge activities in the Greater Los Angeles, California, area. Modified from Hillhouse and others (2002). View of Los Angeles Basin with Landsat overlay, provided by NASA/JPL-Caltech.*

and geophysical data are collected from these and other wells in the area. At selected monitoring sites in the basin, sediment cores from the full length of boreholes are recovered intact when possible. Sediment cores yield various types of information, such as the thickness and grain size of sediment layers; environments of deposition, such as river channels and tidal flats; and chemistry of pore fluids. Geophysical techniques, such as seismic imaging and gravity surveys, are used to interpolate the character of sediments between wells because drilling is so costly. In harbors and offshore areas, a ship-towed system is used to

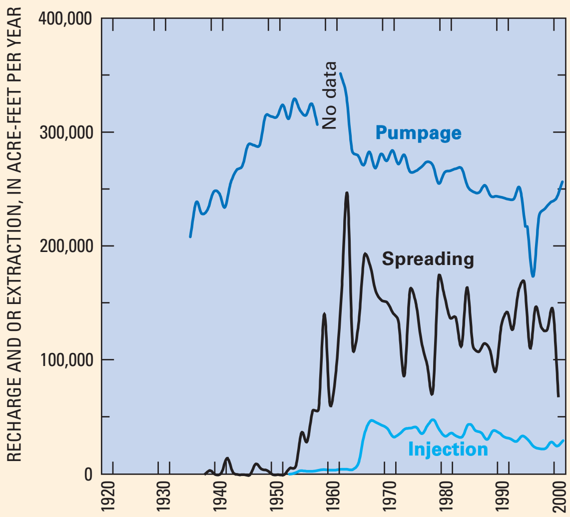


Figure 43. *Pumpage, injection, and spreading in the Central and West Coast Basins, Los Angeles, California. From Reichard and others (2003).*

probe the bottom sediments with acoustic pulses to resolve geologic structure. Data obtained using this range of techniques help to characterize the three-dimensional geologic structure and ground-water flow system of the basin (Edwards and Evans, 2002; Hillhouse and others, 2002).

Chemical and geochemical data are collected to help determine the sources of recharge, the movement and age of ground water, and the fate of the injected water. Extensive hydraulic, geologic, and chemical data were collected from the newly drilled wells (Land and others, 2002). Low-level volatile organic compounds were analyzed in water samples from public-supply wells in the Los Angeles and Orange County area to assess the vulnerability of the wells to contamination (Shelton and others, 2001). These post-industrial-age chemicals can be used to trace the movement of contaminated water. These data and data collected from existing wells were used to characterize the regional geochemistry and geohydrologic framework (Reichard and others, 2003).

The landward advance and position of the saltwater-freshwater interface near the coast is determined by major-ion and other chemical characteristics of water. Sodium chloride water, high in dissolved solids, is present in wells near the coast. Oxygen and hydrogen stable isotope data were collected to provide information on sources of recharge to the basin. Tritium and carbon-14 data provide information on relative ground-water ages. Water that contains abundant tritium (greater than 8 tritium units) is found in and downgradient from the Montebello Forebay, where the extensive artificial recharge (spreading) occurs, and near the seawater-barrier projects, indicating recent recharge. Water containing less than measurable amounts of tritium is present in and downgradient from the Los Angeles Forebay, where no artificial recharge program is in place, and in most wells in the West Coast Basin. Water samples from several deep wells were analyzed for carbon-14. Uncorrected estimates of age for these samples range from 600 to more than 20,000 years before present (Reichard and others, 2003).

A wide variety of inorganic, organic, and isotopic constituents were collected and analyzed in samples from 23 production wells near the Montebello Forebay spreading grounds to ascertain which constituents of wastewater origin could be identified and used as tracers to determine the percentage of recycled water. About 40 water-quality indicators and several physical features, such as well depth and distance from spreading grounds to the production wells, were examined. No one indicator was completely satisfactory as a tracer, although chloride, boron, ultraviolet absorbance at 254 nanometers, and excitation-emission fluorescence seemed to yield the most reasonable estimates. The wastewater signal is present in the water, but the wells draw water from various depths and ages (with variable extent of degradation). This complicates the simple two-member mixing model, making it more difficult to resolve the portions of water from recycled water and from native ground water (Schroeder and Anders, 2002).

A ground-water flow model was developed to simulate conditions in the aquifer system and test water-management strategies. Model results indicate that ground-water storage increases in all parts of the study area over the simulated 30-year period as the result of increased artificial recharge and reduced pumping. Particle tracking was applied to simulate the transport of water from the spreading ponds, the coastline, and the seawater injection barriers. Particle tracking results indicate that most flow within the main producing aquifer system occurs within about 20 percent of the total aquifer thickness and that virtually all water injected into the seawater barrier projects has flowed inland (Reichard and others, 2003).

In order to examine strategies to minimize costs and improve the hydraulic control of seawater intrusion in the West Coast Basin, a simulation-optimization model was developed. Two water-management strategies were evaluated, increased injection and(or) in-lieu delivery of surface water. Assuming constant ground-water demand, in-lieu delivery was determined to be the most cost effective (Reichard and others, 2003).

For more information:
http://water.usgs.gov/pubs/of/ofr01277/

Selected Water-Use Strategies

Conservation.—Conservation as a water-use strategy is commonly proposed as a solution to meet increasing demand. Although seemingly a capitulation to shortage, water conservation holds promise for the future, because in many cases new infrastructure is not required—only a change in user attitudes and practices. Several municipalities in the West, including Tucson, Arizona, Albuquerque, New Mexico, and Austin, Texas, support aggressive water-conservation initiatives including public education concerning the need for and benefits of conservation. Austin and Tucson provide literature on the use of native desert plants to xeriscape residential and business landscapes. Austin also has passed ordinances that limit lawn watering to specified days during periods of high water use and requires that all new business and residential structures be equipped with low-volume plumbing fixtures. The city of Albuquerque promotes a water-conservation program as well called "Water Watch." Tucson Water's efforts to encourage conservation seem to be working. The per capita water use, as measured by the amount of potable water delivered, has declined since 1970 (fig. 44). Municipal water use, without lawns, gardens, swimming pools, or other landscaping, actually uses a nominal volume of water consumptively. The water is returned to the environment, whether a stream or a ground-water aquifer, in a diminished state of water quality.

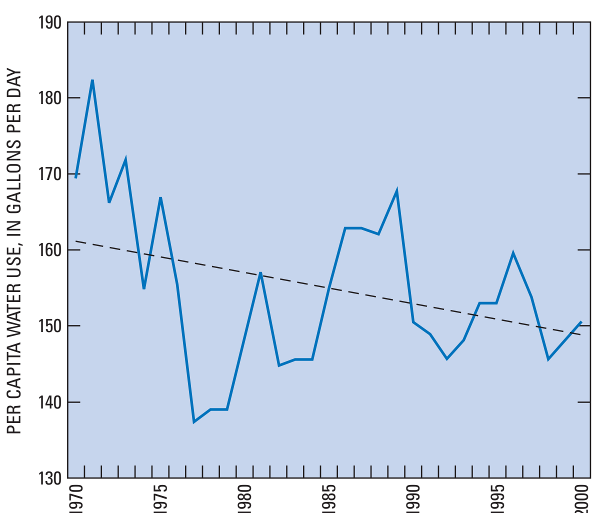


Figure 44. *Trends in per capita delivery of potable water in Tucson, Arizona. (Source: Tucson Water.)*

The U.S. Department of Agriculture and State agricultural extension agencies actively support technology transfer and cost-sharing programs for farm-water-conservation practices and equipment. For example, low-energy precision-application systems are getting widespread use by irrigators in the High Plains. This system distributes irrigation water under low pressure through drop tubes rather than through overhead sprinklers. Other examples of water-conservation practices being supported by agriculture include soil-moisture monitoring to more appropriately time water applications, installation of drip-irrigation systems, and dry farming.

Conjunctive Use.—As water development has evolved, surface water and ground water are used in combination—the most common use in the West today. Despite the knowledge that ground-water and surface-water resources are in fact a single resource, the body of law and administrative statutes treat them as separate resources (Glennon and Maddock, 1994). The linkages between surface water and ground water and the effects of development will need to be better defined to support the strategy of conjunctive use.

The Salt River Project, the water purveyor for Phoenix, Arizona, delivers about 1 million acre-feet per year to water users. It relies first upon the renewable portion of its water supply, which is surface water stored in reservoirs. Ground-water withdrawals from a network of 250 wells are increased when reservoir storage is depleted by seasonal demand or prolonged drought. Similarly, Rapid City, South Dakota, has a series of wells completed in the Madison and Minnelusa aquifers that are used to augment the supply during the winter, when surface-water flows are refilling upstream reservoirs, and especially during periods of drought (Anderson and others, 1999). Thus, strategies that rely first upon surface water, which is the primary renewable portion, and hold ground water in reserve for drought periods, provide greater flexibility .

Natural ground-water recharge can be enhanced by impounding stormflows along normally dry river channels and allowing water to infiltrate into riverbed sediments. In Las Vegas and Phoenix, urban runoff is captured and diverted into so-called dry wells, which are large diameter (6–8 feet) holes up to 100 feet deep that are completed in the unsaturated zone. Runoff from parking lots and streets is diverted into the dry well and allowed to infiltrate into the ground-water system instead of evaporating back into the atmosphere. Similarly, recharge to the Edwards aquifer in south-central Texas is being enhanced within urban and rural settings by instream detention structures within the recharge zone and by shallow drainage wells or improved sinkholes (fig. 45). Artificial replenishment of surface-water supplies, either by interbasin transfer or return flow in the form of treated effluent, is becoming a common conjunctive-use strategy. Other potential strategies include the construction of artificial aquifers, in which a membrane-lined depression is filled with an artificial medium, such as coarse gravel, and covered to eliminate evaporation. Again, stormwater runoff or imported water is allowed to percolate into the medium and to be withdrawn as needed. The issue of biofouling of the media is less of a concern when the strategy is used because the media at the point of recharge is normally dry.

Figure 45. *Flood runoff diverted by an engineered channel from Seco Creek to an improved sinkhole that penetrates the Edwards aquifer, Medina County, Texas, July 8, 2002. Photograph provided by San Antonio Water Systems.*

Water Reuse.—There is now wider interest in and economic benefits to reusing municipal wastewater rather than directly returning it to the environment. Some industries and power-generation facilities that use large amounts of water are now co-locating with municipal treatment plants to facilitate the use of treated effluent for cooling and process water. Other reuse practices include low-rate land spreading on golf courses and right-of-ways. The Los Angeles County Sanitation District, for example, is rapidly expanding the number of sites and volume of nonpotable wastewater effluent reused within their service area (fig. 46). Some residential developments have encouraged gray-water systems, whereby new homes are equipped with a separate plumbing system to collect wash water from the kitchen and laundry drains. The gray water is used for watering residential landscapes.

Desalination.—In 1990, 50 percent of the Nation's population lived within 47 miles of a coast, but that number is projected to increase to 75 percent by the year 2010 (Williams and others, 1990). This narrow fringe along the coasts constitutes less than one-fifth of the contiguous United States land area, but accounts for more than one-half of the Nation's housing supply. The population of these coastal areas grew by more than 38 million people between 1960 and 1990 (Culliton and others, 1990; Zinn, 1997).

The tantalizing prospect of securing an unlimited, drought-proof supply of freshwater from the ocean has historically encountered the sobering reality of cost. The cost of converting seawater to freshwater is five to six times that of treating freshwater (Bureau of Reclamation, 1999). Advances in technology (membrane filtration, electrodialysis reversal, and reverse osmosis) are driving down the cost of desalination (fig. 47). Dewvaporation is an atmospheric-pressure desalination process that is a relatively new heat-efficient tower process. The process uses a humidification-dehumidification approach in which air is used as a carrier gas to evaporate water from saline source water and dew to form pure condensate

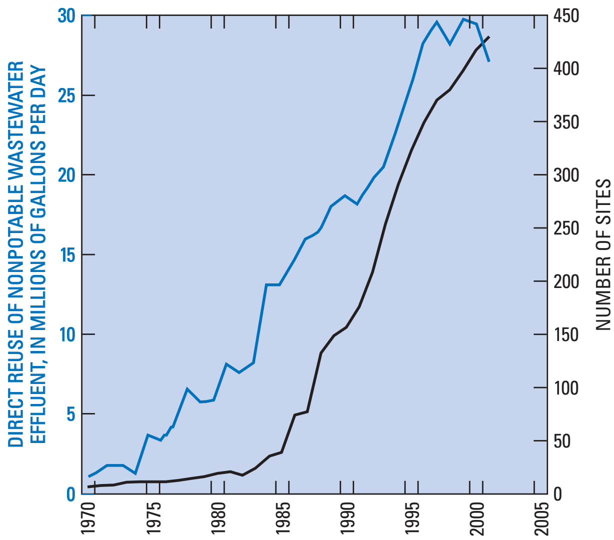


Figure 46. *Increase in the number of sites using treated wastewater and volume of treated wastewater reused in Los Angeles County, California, 1970 to 2001. (Source: Los Angeles County Sanitation District.)*

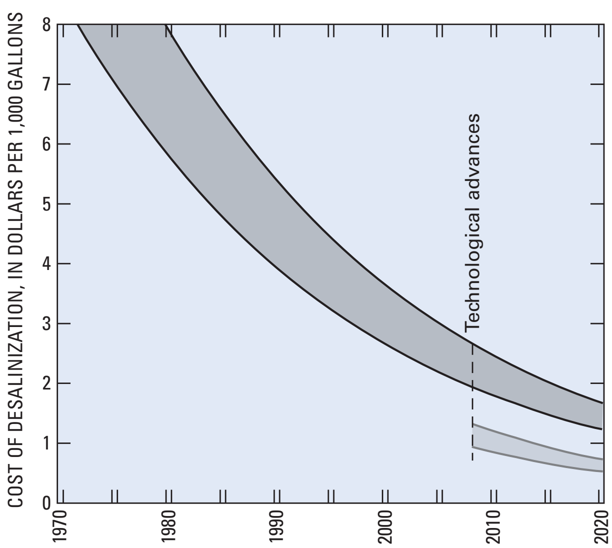


Figure 47. *Declining costs of desalinization. (Source: Bureau of Reclamation and Sandia National Laboratories, Albuquerque, New Mexico.)*

Water	Concentration of salts, in thousands of milligrams per liter
Freshwater	Less than 1
Slightly saline	1–3
Moderately saline	3–10
Very saline	10–35
Seawater	35

at constant atmospheric pressure. Initial testing suggests that the average operating costs for brackish and seawater desalination for small plants of $3.35 per 1,000 gallons can be reduced to $1.55 per 1,000 gallons using dewvaporation (Beckman and Hamieh, 2000). This lowering of cost and the difficulty of securing conventional freshwater supplies are making desalination more feasible. Ten communities in California and four in Texas are proposing or supporting desalination facilities.

Brackish water is available in many inland areas of the West and with some treatment could relieve stress on limited freshwater supplies. Vast inland areas of the Western United States are underlain by aquifers containing brackish or slightly saline water (greater than 1,000, but less than 35,000 milligrams per liter; fig. 48). The reduced cost of desalination for brackish water is offset, however, by the issue of waste-brine disposal. Disposal pipelines (brine lines) to deliver the waste stream from inland locations to an ocean are prohibitively expensive, making it impractical to secure permits, easements, and facility costs. A technological advance is needed to find economical ways to solidify the salts from the brine before desalination can be brought into common use for inland areas.

For many municipalities, salts are enriched as they are cycled through the distribution system, collected again, treated in the wastewater-treatment process, and recharged back into an aquifer. Treated effluent is usually about one-third more saline than the influent water delivered to the water user as potable water.

"New authorizations are needed to encourage drought preparedness planning, improve drought monitoring and forecasting, and shift federal investment away from response programs to proactive drought mitigation,"
—Western Governors' Association letter to Congress, July 24, 2003

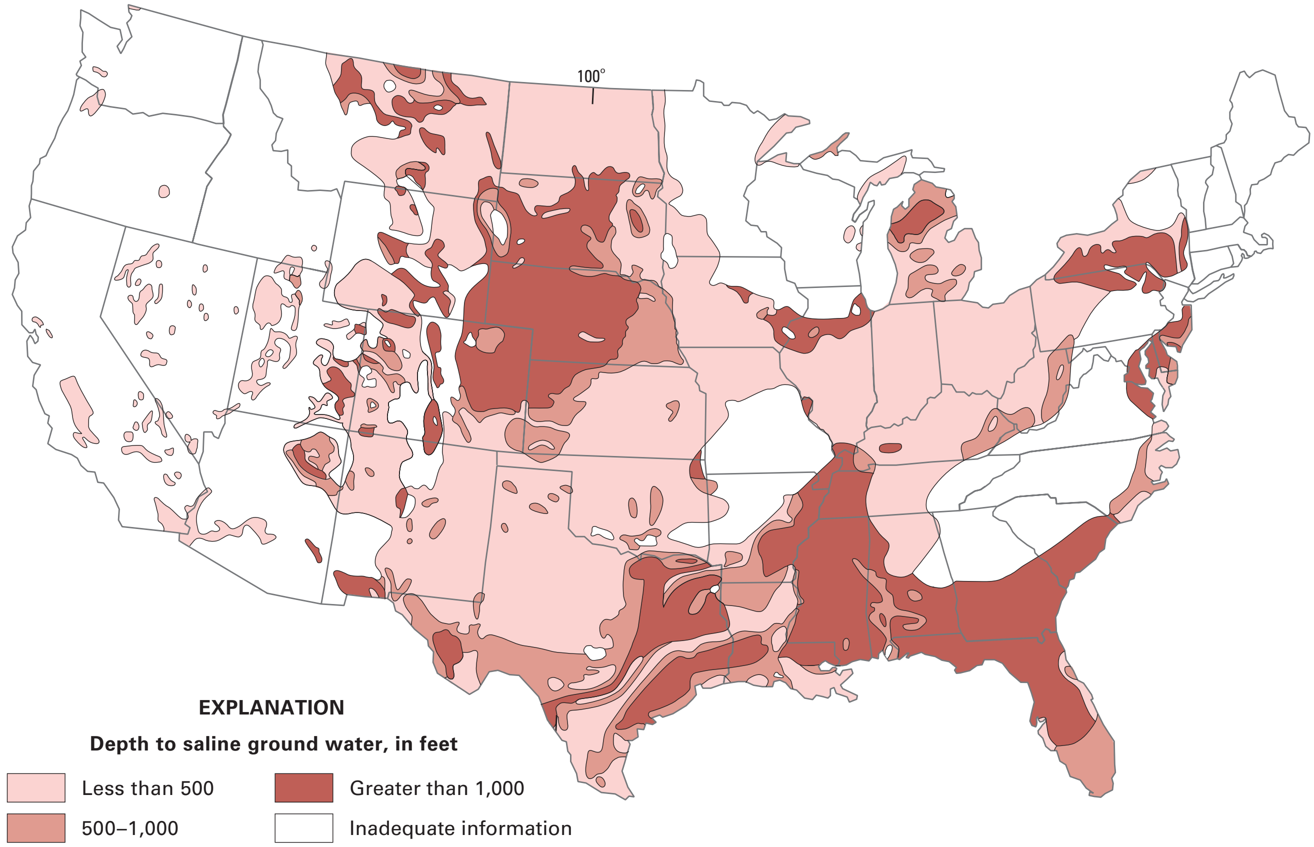


Figure 48. *Depth to saline ground water for the contiguous United States. From Feth and others (1965).*

The scientific information useful to support these various water-use management strategies is quite varied, and only a few of the key challenges are discussed here. In all cases, water-use data are useful in providing objective feedback mechanism on the efficacy of these strategies. The challenge for science in support of conservation, conjunctive use, water reuse, and desalination is to facilitate technological advances and provide the facts to help change consumer attitudes. Water reuse will hinge on the occurrence, transport, and fate of pathogenic organisms and the wide array of organic wastewater contaminants.

The challenge for science in support of conjunctive use will be to develop the monitoring capabilities and the tools to manage the water resources more holistically. In Arizona, the State Supreme Court has ruled that water drawn from shallow wells completed in the sands and gravels along a stream, defined as the Holocene alluvium, is surface water and, therefore, subject to appropriation. The Court used the term "subflow" to describe these surface waters. An objective science-based method is needed to provide a means to differentiate subflow, wherever it occurs, from water drawn from other geologic materials. Furthermore, predictive models that more accurately represent the connections between surface water and ground water are needed.

The challenge of science in support of desalination is to characterize the potential sources of brackish and inland saline water in ground-water reservoirs.

Scientists will be asked to provide information to help answer questions such as: How much brackish water is available? What is its geochemical composition? What will be the consequences of developing this resource? The development of brackish or saline ground water will introduce all the same potential consequences as the development of freshwater from aquifers. The disposal of the waste brine from inland desalination activities may be a limiting factor in this water-use strategy, and science will be required to find cost-effective solutions. More detail on the types of scientific information useful to conservation, conjunctive use, water reuse, and desalination is presented in table 5.

Sustaining Valued Ecosystems

Society's desire to maintain or restore ecosystems and individual species has given strength to the ESA. Because water is a critical habitat requirement for many endangered species, the water-management alternatives in the West often are driven by, or framed by, the ESA. Sustaining restored and existing ecosystems will require more scientific knowledge and understanding than is presently available.

One of the great scientific challenges will be to assess ecosystem health and determine anthropogenic effects on what is an already human-altered system in a consistent and comparable manner. The questions that often are asked are: What is the reference for comparison? And, what is achievable? For example, it was normal for some Western streams to flow only during parts of the year. With the construction of a reservoir, perennial cool water now may create another type of ecosystem immediately downstream from the dam, and the reservoir itself creates another type of ecosystem. Before an ecosystem can be assessed, agreement is needed on what is benchmark or reference for comparison and what type of ecosystem society wishes to maintain. Feedback mechanisms are needed to assess whether well-intended mitigative measures are helping or adversely affecting ecosystem health.

On a much larger scale, the health of the Nation's ecosystems and associated trends should be tracked and reported. The Heinz Center released a report entitled, "The State of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States" that suggests how ecosystem health can be assessed (H. John Heinz III Center for Science, Economics, and the Environment, 2002).

Scientific Information

Key indicators of the health of the Nation's ecosystems are needed in addition to a reporting system of any trends. Multidisciplinary science teams will be asked to take on this challenge of assessing ecosystem health, which would involve establishing appropriate reference conditions for comparison purposes. The determination of specific habitat requirements for individual plant and animal species requires collaboration by the physical and biological sciences on standardized and integrated field and laboratory investigations—an approach often discussed but seldom practiced.

In the past, hydrologic investigations were usually developed to address local problems or issues. In the future, more holistic approaches are required that consider an entire watershed (as John Wesley Powell suggested more than 100 years ago) and address the complex interactions between the surface-water and ground-water systems. Models that can predict the effects of utilization of one resource upon the other are needed. For example, ground-water models typically are prepared to describe the flow in response to ground-water pumping, but seldom is the linkage made to the potential effects on base flow in a hydrologically connected stream or on water levels in a wetland.

A carefully designed program of monitoring and investigation is needed, particularly where aquifers are intensively managed or high-valued ecosystems are at risk. Systematic data collection is needed to determine trends—Are things getting better or worse, and by how much? Systematic data collection also serves as an important feedback mechanism on the effectiveness of alternative-management strategies and mitigation measures implemented, often at great expense.

CASE EXAMPLE—*San Pedro Riparian National Conservation Area, Arizona*

The San Pedro Basin in southern Arizona is a case exmple on the complicated interplay of ground-water and surface-water interactions, ecosystem management, and endangered species (fig. 49). The San Pedro River is one of the last remaining desert streams with perennial reaches and a vigorous riparian area that supports a wide diversity of flora and fauna. The city of Sierra Vista, the adjacent U.S. Army base, Fort Huachuca, and many rural residents pump ground water as their sole source of water supply.

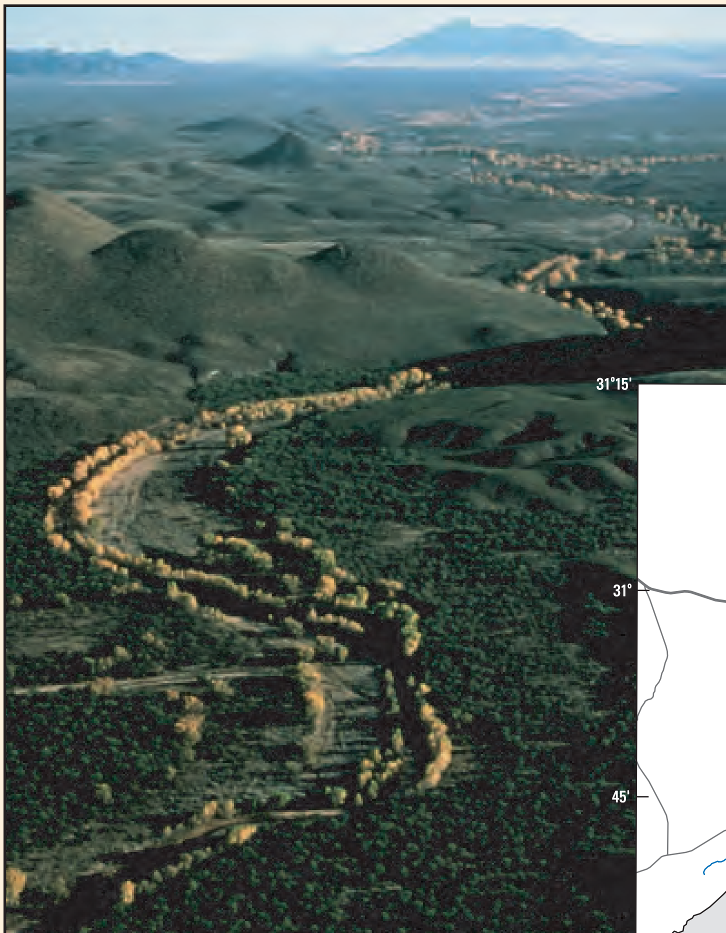
There is concern that this pumping eventually will diminish or convert the San Pedro from a perennial to an ephemeral stream. Congress designated a portion of the San Pedro Basin as the San Pedro Riparian National Conservation Area (SPRNCA) in 1988. SPRNCA is now managed by the Bureau of Land Management (BLM). The BLM has the management responsibility of sustaining the ecosystem in the Nation's first national riparian area for future generations. Water, perennially flowing in the river, and ground-water levels at the vegetative root zones are key to sustaining the ecosystem.

The water-availability concerns shared by many agencies, organizations, and residents gave rise to the Upper San Pedro Partnership (USPP). The USPP is a consortium of 21 agencies and organizations formed to ensure that the long-term water needs of the Upper San Pedro Basin are met. They have established a planning goal to "ensure an adequate long-term ground-water supply is available to meet the reasonable needs of both the area's residents and property owners (current and future) and the San Pedro Riparian National Conservation Area" (Russell Scott and others, U.S. Department of Agriculture–Agricultural Research Service, written commun., 2002).

One of the riparian plants of concern is the Huachuca water umbel (*Lilaeopsis schaffneriana* spp. *Recurva)*—a plant found in and along the San Pedro River and in cienegas (desert marshes) and springs in southern Arizona and northern Sonora, Mexico (fig. 50). The U.S. Fish and Wildlife Service designated critical habitat including the San Pedro River in Cochise County, Arizona (U.S. Fish and Wildlife Service, 1999). The Secretary of the Interior is required to apply the best scientific information available to determine the critical habitat requirements for this plant.

Scientific Information Collected.— Three agencies (U.S. Department of Agriculture–Agricultural Research Service, Arizona State University, and USGS) are working together to characterize the water requirements of the San Pedro riparian system (James Leenhouts, U.S. Geological Survey, written commun., 2003). The intent of the SPRNCA Water Needs study is not only to define the hydrologic requirements of the SPRNCA itself, but also to provide information regarding the potential management actions that could be used to reduce the consumptive water uses within the SPRNCA without causing any negative effects on the riparian resources.

The study has three objectives: (1) to determine the temporal and spatial water needs of riparian vegetation, (2) to quantify the total consumptive water use of riparian vegetation, and (3) to determine the sources of water consumed by key riparian plant species. The data-collection program includes monitoring the evapotranspiration fluxes above a mature, mesquite woodland and basic meteorological variables (air temperature, relative humidity, incident solar radiation, windspeed and direction, air pressure, and precipitation) that drive the evaporation process. Water content in the vadose zone is measured using borehole ground-penetrating radar to determine if mesquite trees are able to redistribute water downward. Additionally, sap-flow sensors have been installed on the lateral roots and main taproot of several mesquite trees to determine the magnitude and direction of flow within them throughout the year (Russell Scott and others, U.S. Department of Agriculture–Agricultural Research Service, written commun., 2003).



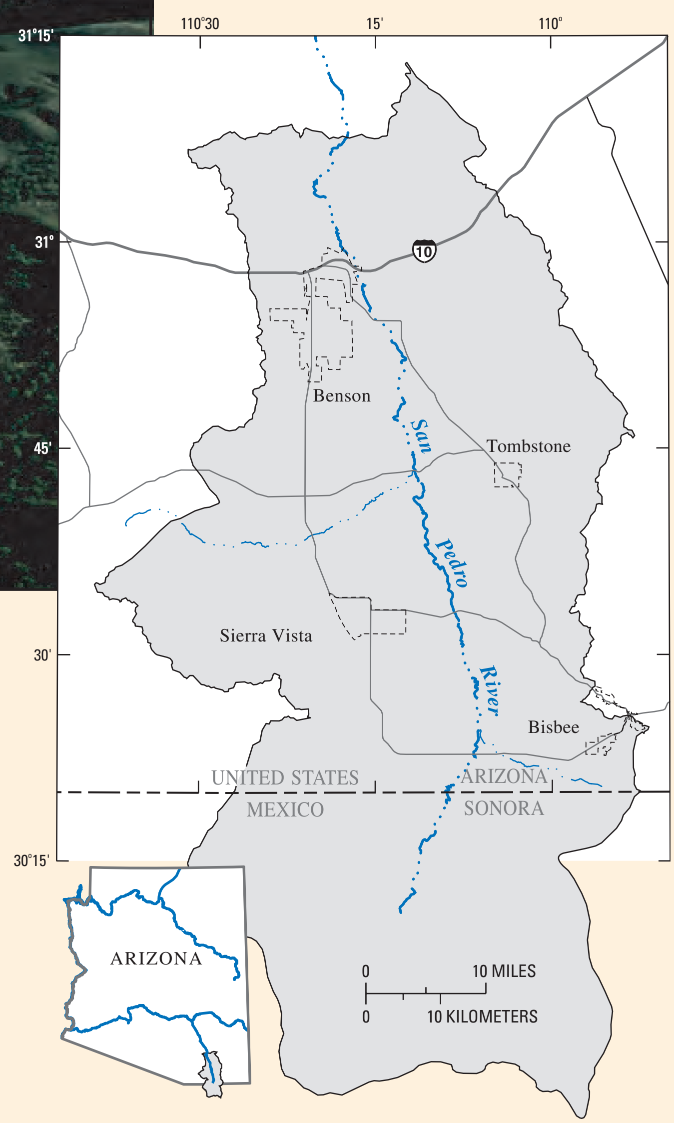


Figure 49. *The San Pedro River Basin in southern Arizona—a valued ecosystem. Photograph of the San Pedro River looking south toward Mexico provided by Marty Cordano, Bureau of Land Management.*

***Figure 50.** Huachuca water umbel (Lilaeopsis schaffneriana* spp. *Recurva). (Source: U.S. Fish and Wildlife Service.)*

Estimates are made of the water-use patterns or transpiration requirements of cottonwood as inputs to an evapotranspiration (ET) model. Cottonwood trees of varied diameters were instrumented with sap-flow sensors. Sap flow was measured in each tree using a thermal-dissipation probe implanted on each tree at 5.7 feet above the ground (Goodrich and others, 2000). Oxygen and hydrogen stable isotope data are being used to help identify the source of water being transpired by the trees (ground water or recent precipitation).

Species diversity and biomass structure of the vegetation are assessed at biohydrology sites (sites instrumented by the USGS with piezometers and stage recorders). The study is developing a prototype Index of Riparian Condition. A suite of vegetation traits (indicators), which are sensitive to streamflow and(or) ground-water conditions, were identified to include in the index. The indicators include various measures of species composition, diversity, and biomass structure. Basic hydrologic data were collected, including ground-water levels measured in piezometers, stream-stage and discharge measured at study transects, and topographic surveys of stream profiles. Flood inundation frequencies are calculated for various levels along each biohydrology transect. Data are archived in the appropriate parts of the USGS national database (NWIS, *http://waterdata.usgs.gov/nwis/sw/*). In addition to the water levels, these data include well location, elevation, screen depth, and other related information (Russell Scott and others, U.S. Department of Agriculture–Agricultural Research Service, written commun., 2003).

The data-collection and research efforts are expected to quantify the total consumptive ground-water use from the regional aquifer by riparian vegetation within SPRNCA. In addition, a GIS-based management tool will help determine how changes in riparian-vegetation composition will likely alter the total consumptive regional aquifer ground-water use of riparian vegetation.

For more information:
http://www.usppartnership.com/
http://www.tucson.ars.ag.gov/salsa/research/research.html/
http://policy.fws.gov/library/99fr18596.html/
http://www.co.pima.az.us/cmo/sdcp/sdcp2/fsheets/hwu.html/

Sustaining Individual Endangered Species

Flow management of major Western rivers is altered to favor the survival of individual endangered species, such as the humpback chub in the Colorado, spring chinook salmon in the Columbia, silvery minnow in the Rio Grande, and splittail minnow in the Sacramento (fig. 30). Even endangered bird species are constraining river and reservoir management by nesting in vegetation that has invaded exposed mudflats of depleted reservoirs. The southwestern willow flycatcher (*Empidonax traillii extimus*) prefers nest sites in riparian vegetation. After flycatchers have nested in the reservoir, allowing reservoir levels to return to normal is considered a "taking" of habitat by the ESA, even though storing water in the reservoir was the original purpose of the facility. Nevertheless, the Salt River Project purchased an equivalent acreage of flycatcher habitat away from the reservoir to avoid a violation of the ESA for this listed species. Conservation efforts to recover individual species from the brink of extinction are complicated and potentially expensive as the following examples illustrate.

A few years ago, the mere suggestion of dam removal for ecosystem restoration was considered an extremist thought. The U.S. Army Corps of Engineers released a draft Biological Opinion in which the removal of four dams (Lower Granite, Little Goose, Lower Monumental, and Ice Harbor) on the Snake River in Washington was considered as an alternative for recovery of the endangered spring chinook salmon (U.S. Department of Commerce, 2000). Dam removal was not selected as the preferred alternative because the scientific evidence was not sufficient to provide the assurance that recovery would be achieved even if such costly steps were taken. The strategy proposed was to exercise all other promising (and less costly) measures first. National Marine Fisheries Service has applied a matrix model to the long-term population data and found that dam-passage improvements have dramatically mitigated direct salmon mortality associated with dams (Kareiva and others, 2000). Even if main-stem survival of migrating adults were increased to 100 percent, however, Snake River spring/summer chinook salmon would continue to decline toward extinction (Kareiva and others, 2000). Hence, the current practice is to barge juvenile salmon around dams, rather than resorting to dam removal. Interestingly, the dams will stay for now, not solely for their value to society for hydropower generation or other economical considerations, but because the scientific evidence is inconclusive about the benefits to salmon recovery—a remarkable shift of society's values. Some dams are being retrofitted with vented turbines and oxygen injection systems to increase the concentration of dissolved oxygen in tailwaters that consist of oxygen-depleted water released from the lower depths (hypoliminon) of the reservoirs. The recovery of Pacific Northwest salmon will depend upon quantitative scientific information about their physical habitat requirements.

Sockeye salmon crossing shallow gravel bar to spawn, Hansen Creek, Alaska. (Photograph provided by Thomas P. Quinn, School of Aquatic and Fishery Sciences, University of Washington, Seattle.)

The habitat requirements of individual species are difficult to specify, let alone quantify. Instream flow rights for fish habitat often specify a volume of water, which is a complex determination (fig. 51). In the case of the humpback chub, their critical habitat requirement may not be a minimum flow, but rather the water-temperature regime or even turbidity. The chub's competitive advantage over other species under natural conditions in the Colorado River may have been removed by the clear-water releases from Glen Canyon Dam. In the case of the Kanab ambersnail at Vaseys Paradise in the Grand Canyon, controlled flooding cannot exceed 45,000 cubic feet per second. Because the flood in 1996 scoured away an estimated 10 percent of the snail's preferred habitat, future controlled floods could not exceed 45,000 cubic feet per second until a second population of snails was established elsewhere in the canyon—no matter how effective high flows are at restoring other aspects of ecosystem function (Schmidt and others, 1998). The controlled flood of 1996 was half the average annual peak discharge before the dam. There is insufficient experience and historical precedent in Western water law to find amicable solutions in these conflicts. These examples illustrate the complexity and need for quantitative information when prescribing restoration solutions for individual species.

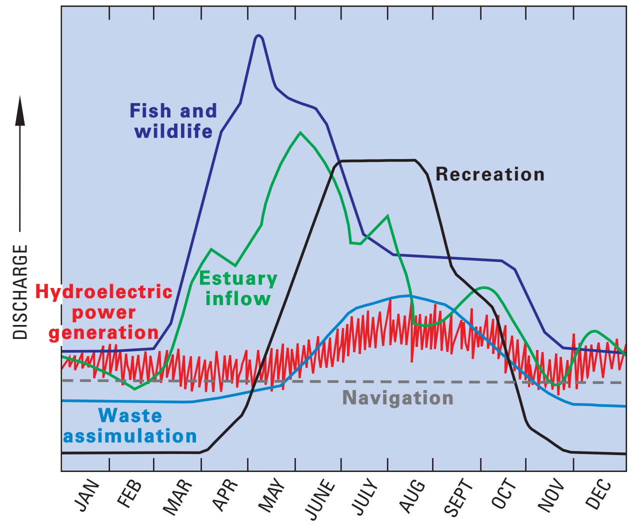


Figure 51. *Relative streamflow requirements for instream-flow uses throughout a calendar year. From Carr and others (1987).*

Vaseys Paradise in Grand Canyon, Arizona, habitat of the endangered Kanab ambersnail. Photograph by Mark T. Anderson, U.S. Geological Survey.

Scientific Information

The challenge for science will be to determine the physical habitat requirements of selected individual species. The management and recovery of endangered species requires knowledge of population dynamics. It is difficult to determine trends of biological populations, especially those of endangered species because of their small populations and natural variability. The ability to know whether a species is in recovery or slipping closer to extinction is a critical bit of knowledge to know when trying to determine whether mitigation measures are effective. In addition to the population trends, other details of the physical habitat requirements of individual species will need to be quantified. Some physical habitat usually is considered critical for a given species, for example, water temperature, turbidity, sediment transport, nutrient concentrations, or even minimum water levels. New ways of conducting investigations are needed in which genuine interdisciplinary results are produced that integrate the biological and physical sciences. The following case example of the Upper Klamath Lake provides some insights into the need for quantitative information.

CASE EXAMPLE—*Upper Klamath Lake, Oregon, Lost River and Shortnose Suckers*

Upper Klamath Lake is a large, shallow lake in southern Oregon and is a major source of water to the Klamath River, which flows through Northern California into the Pacific Ocean (fig. 52). The Lost River sucker (*Deltistes luxatus*) and the shortnose sucker (*Chasmistes brevirostris*) (fig. 53), once abundant in Upper Klamath Lake, were placed on the endangered species list in 1988 (U.S. Fish and Wildlife Service, 1988) because their populations were declining.

Upper Klamath Lake probably was eutrophic when first discovered by non-Indian settlers in the 1800s; however, beginning around 1900, the lake has progressed to a hypertrophic condition characterized by increases in algal abundance and changes in algal composition (Bortleson and Fretwell, 1993). A possible cause for the increased abundance of algae is an increase of agricultural related nitrogen and phosphorus compounds in surface-water inflows into the lake. When massive blooms of blue-green alga, *Aphanizomenon flos-aquae,* die-off, a short-term, high dissolved-oxygen demand is produced, and oxygen concentrations can decrease to less than 2 milligrams per liter, with an increase in ammonia concentrations. The high productivity of algae increases pH to greater than 9.5 and increases turbidity, resulting in poor environmental conditions for the indigenous sucker populations (Bortleson and Fretwell, 1993). Seven major die-off events of suckers have occurred since 1960 (U.S. Fish and Wildlife Service, 2001). Reduction in the abundance of the suckers is attributed to changes in water quality, but also to excessive harvesting, introduction of exotic fish, alteration of flows, entrainment of fish into water-management structures, and physical degradation of spawning and rearing areas (U.S. Fish and Wildlife Service, 2001).

Figure 52. *Location of Upper Klamath Basin, Oregon. Photograph of Upper Klamath Lake provided by Oregon Natural Resources Council.*

Figure 53. *The endangered fishes of Upper Klamath Lake, Oregon. The top photograph is the shortnose sucker and the bottom photograph is the Lost River sucker. Photographs by Rollie White, U.S. Fish and Wildlife Service.*

Competition for water in the Upper Klamath Basin has increased in recent years partly because of growing demand for water for aquatic wildlife and other instream uses. These demands are in addition to the traditional uses of water for irrigation. Managing existing water supplies to fully satisfy all uses has proven difficult, particularly during dry years. As resource managers work to sustain water supplies for irrigation and fisheries habitat, there is broad interest in exploring the use of ground water to alleviate water-supply issues in the basin. Ground water historically has been used to supplement surface water for irrigation during dry years. Increases in ground-water pumping, however, may eventually deplete flow to streams and tributary springs.

On the basis of low snowpack and low precipitation, the U.S. Natural Resource Conservation Service predicted (in early spring 2001) extreme low-flow conditions for the Upper Klamath Basin for the summer of 2001. To protect the endangered Lost River and shortnose suckers, the U.S. Fish and Wildlife Service issued a Biological Opinion asking Reclamation to maintain a minimum elevation of Upper Klamath Lake (U.S. Fish and Wildlife Service, 2001). In another Biological Opinion, from the National Marine Fisheries Service, Reclamation was asked to ensure minimum flows in the Lower Klamath River to provide adequate habitat for Coho salmon (National Marine Fisheries Service, 2001). Coho stocks in the Southern Oregon/Northern California coasts already were listed as a threatened species under the ESA by the National Marine Fisheries Service (1997). To ensure an adequate volume of water throughout the summer of 2001 that could be used to maintain the lake elevation and provide established minimum flows, Reclamation curtailed nearly all deliveries of water to the irrigators in the Klamath Project. Substantial agricultural losses occurred, along with damage to the economic base of the Klamath Basin. Given the strong economic consequences of implementing the Biological Opinions on the Klamath Project, the U.S. Department of the Interior determined that the scientific basis for the two opinions should be reviewed. The National Research Council (NRC) was asked to conduct a re-evaluation, and it concluded in their interim report that the scientific evidence presented in the Biological Opinions was insufficient to connect minimum lake elevations to adverse welfare of the suckers (National Research Council, 2002).

In early spring of 2002, extreme low-flow conditions again were predicted for the Upper Klamath Basin for the summer of 2002. Taking the NRC interim conclusion into account, Reclamation decided to provide water to irrigators for the summer of 2002 at the normal pre-2001 levels. The full delivery of water for irrigation resulted in lower water levels in Upper Klamath Lake and reduced downstream flows. In September 2002, a minimum of 33,000 adult salmon and steelhead trout, returning to spawn, died mostly within the lower 36 miles of the Klamath River. Biologists of the California Department of Fish and Game determined that the cause of death was infection by protozoan and bacteria pathogens (California Department of Fish and Game, 2003). The spread of these diseases can be exacerbated by low-flow, high water temperature, and crowding of fish. The existence of these conditions in a stream does not necessarily mean that an epidemic will occur, but they do increase the risk. An overview of the hydrologic conditions prior to the fish die-off is described by Lynch and Risley (2003).

Scientific Information Collected.— Many State, Federal, and tribal agencies and other organizations are collecting data in the Klamath Basin. The biological opinions of the U.S. Fish and Wildlife Service (2001) and the National Marine Fisheries Service (2001) contain valuable literature reviews for the area. A few examples of the types of data collected in support of endangered species concerns are presented here. The USGS monitors streamflow into Upper Klamath Lake.

Reclamation and the Klamath Tribes have been collecting water-quality data in Upper Klamath and Agency Lakes since 1988. These data indicate that dissolved-oxygen concentrations low enough to be of concern most likely are to occur in late summer, after large algal blooms have started to decline. The lowest dissolved-oxygen concentrations most likely are to occur near the bottom of the water column; however, low dissolved-oxygen concentrations have been measured at and near the water surface as well (Wood, 1999).

Nutrient loading into the lake from adjacent wetlands (Snyder and Morace, 1997) and the role of reservoir regulation on flushing patterns have been investigated by the USGS for the lake's two major tributary basins, the Williamson/Sprague and Wood. The nutrient flux to the lake was assessed by a fixed station and synoptic sampling in addition to measurements of discharge. Reclamation and the Klamath Tribes periodically assess the nutrient loading to the lake from small streams, ditches, and canals (Joseph Rinella, U.S. Geological Survey, written commun., 2003).

A multiyear investigation of the ground water of the Klamath Basin is underway (Marshall Gannett, U.S Geological Survey, written commun., 2003). A phase of intensive data collection and well inventories will be followed by the development of a numerical ground-water flow model to simulate ground-water conditions under various management scenarios. The model will be paired with optimization techniques to identify water-management solutions for conjunctive use of ground water and surface water (Gannett, 2003).

The link between the physical habitat and the welfare of the endangered suckers is being investigated by studying the movements of radio-tagged fish. The role of "water-quality refugia," or limited locations in the Lake where temperatures and oxygen levels are sufficient for survival, is thought to be critical for adult sucker survival in Upper Klamath Lake. The USGS is studying the behavioral response of suckers to the distribution of poor- and better quality water in the northern part of the lake. About 100 adult suckers were tagged (targeting equal numbers of Lost River and shortnose suckers of each sex) with digitally encoded, programmable transmitters that can be turned on from about February to October. Water-quality profiles associated with individual locations of radio-tagged suckers are collected. A network of water-quality monitoring stations (11–14 sites) provides previously unattainable detail on the spatial and temporal variability of water-quality refugia in the northern part of Upper Klamath Lake. The data from the fixed stations form the basis of a GIS spatial and temporal model of the water-quality conditions in the northern part of the lake (Tamara Wood, U.S. Geological Survey, written commun., 2003).

For more information:
http://oregon.usgs.gov/pubs_dir/Online/Hrml/OFR95-285/klamath_bib.html/
http://www.mp.usbr.gov/kbao/esa/
http://oregon.usgs.gov/projs_dir/pn381/pn381.html/

Conclusions

This report provides a description of the history of the water development and examines water availability and the factors that complicate water management for the Western United States. The needs for scientific information as the population in the West continues to grow also are presented. The challenge today is to sustain water availability perpetually, not only for human use, but to sustain ecosystems and critical habitat for flora and fauna. Not since John Wesley Powell's visionary report on the arid lands of the United States (Powell, 1878) has there been a broad scientific assessment of the availability of water for the West. Such assessments are needed periodically, but more sophisticated information is needed to devise effective water-use and -management strategies on the basis of good science. The National Research Council (2001a) has noted the deficiency in the way science is conducted in support of water policy—too fragmented and unable to anticipate the management challenges and scientific questions. The assessment in this report is not complete or comprehensive because, in most instances, the data are unavailable, but the types and kinds of scientific information useful to make decisions is discussed by examining some of the current issues facing Western water managers.

Science has an important role to play in meeting these water-availability challenges. The right information needs to be collected systematically across the West and made publicly available, the proper tools developed, and the objectivity of the science agency conducting the work must be guarded. When conflict arises over the highest and best use of available water, science cannot be invoked to create harmony, but it can facilitate better and more informed decisionmaking. Today, securing and managing water supplies is far more complicated than in the past. The role of science in helping to meet water challenges will not likely involve finding undiscovered sources of water, but rather will be integral in developing a more comprehensive understanding of the consequences of each course of management action.

References

Alley, W.M., 2001, Ground water and climate: Ground Water, v. 39, no. 2, p. 161.

Alley, W.M., and Leake, S.A., 2004, The journey from safe yield to sustainability: Ground Water, v. 42, no. 1, p. 12–16.

Alley, W.M., Rielly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 86 p. URL *http://water.usgs.gov/pubs/circ/circ1186/*

Anderson, M.T., Driscoll, D.G., and Williamson, J.E., 1999, Ground-water and surface-water interactions along Rapid Creek near Rapid City, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98–4214, 99 p.

Aspen Institute, 2002, Dam removal—A new option for a new century: Washington, D.C., The Aspen Institute, accessed August 4, 2003, at URL *http://www.aspeninstitute.org/AspenInstitute/files/CCLIBRARYFILES/FILENAME/0000000074/damremovaloption.pdf/*

Bortleson, G.C., and Fretwell, M.O., 1993, A review of possible causes of nutrient enrichment and decline of endangered sucker populations in upper Klamath Lake, Oregon: U.S. Geological Survey Water-Resources Investigations Report 93–4087, 24 p.

Bush, Vannevar, 1945, Science, the endless frontier, a report to the President by the Director of the Office of Scientific Research and Development, July 1945, United States Government Printing Office, Washington, D.C.: Reprinted 1990, National Science Foundation, accessed August 4, 2003, at URL *http://www.nsf.gov/od/lpa/nsf50/vbush1945.htm*

Barlow, P.M., and others, 2002, Concepts for national assessment of water availability and use: U.S. Geological Survey Circular 1223, 34 p. URL *http://water.usgs.gov/pubs/circ/circ1223/*

Barroll, Peggy, 2001, Documentation of the administrative groundwater model for the Middle Rio Grande basin: Santa Fe, New Mexico Office of the State Engineer, Hydrology Bureau Report 99–3, 22 p.

Barry, J.M., 1997, Rising tide—The great Mississippi flood of 1927 and how it changed America: New York, Simon and Schuster, 481 p.

Bartolino, J.R., 2002, How ground-water/surface-water interaction of the Rio Grande has been studied, *in* Bartolino, J.R., and Cole, J.C., Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, p. 78–79. URL *http://water.usgs.gov/pubs/circ/2002/circ1222/*

Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, 145 p. URL *http://water.usgs.gov/pubs/circ/2002/circ1222/*

Bartolino, J.R., Cole, J.C., and Hester, D.J., 2002, Groundwater resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Fact Sheet FS–088–02, 6 p.

Bartolino, J.R., and Constantz, Jim, 2002, How mountain-front recharge is studied, *in* Bartolino, J.R., and Cole, J.C., Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, p. 74–75.

Bauer, P.W., 2001, Geologic mapping in New Mexico: New Mexico Earth Matters, v. 1, no. 2, p. 1–4.

Beckman, J.R., and Hamieh, B., 2000, Carrier-gas desalination analysis using humidification-dehumidification cycle: Chemical Engineering Community, v. 177, p. 183–193.

Bortleson, G.C., and Fretwell, M.O., 1993, A review of possible causes of nutrient enrichment and decline of endangered sucker populations in Upper Klamath Lake, Oregon: U.S. Geological Survey Water-Resources Investigations Report 93–4087, 24 p.

Bredehoeft, J.D., Papadopulos, S.S., and Cooper, H.H., 1982, Groundwater—The water budget myth, *in* Studies in geophysics, scientific basis of water resource management: Washington, D.C., National Academy Press, 127 p.

Brownell, D.L., and Rinallo, M.R., 1995, A selected bibliography of water related research in the Upper Klamath basin, Oregon: U.S. Geological Survey Open-File Report 95–285, 23 p. URL *http://pubs.er.usgs.gov/pubs/ofr/ofr95285*

Bureau of Reclamation and Sandia National Laboratories, 2003, Desalination and water purification technology roadmap—A report of the executive committee: Desalination and Water Purification Research and Development Program Report 95, 61 p.

Buxton, H.T., and Kolpin, D.W., 2002, Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams: U.S. Geological Survey Fact Sheet FS–027–02, 2 p. URL *http://toxics.usgs.gov/pubs/FS-027-02/*

California Department of Fish and Game, 2003, September 2002 Klamath River fish kill—Preliminary analysis of contributing factors, 67 p. URL *http://www.dfg.ca.gov/html/krfishkill-rpt.pdf*

California Environmental Resource Evaluation System, 2002, Water rights in California, accessed August 4, 2003, at URL *http://ceres.ca.gov/theme/env_law/water_law/water_rights.html/*

Campbell, Paul R., 1996, Population projections for States by age, sex, race, and Hispanic origin—1995 to 2025: U.S. Bureau of the Census, Population Division, PPL–47.

Cappaert v. *United States*, 426 U.S. 128 (1976).

Carlson, C.A., and Muth, R.T., 1989, The Colorado River—Lifeline of the American Southwest, *in* Dodge, D.P., ed., Proceedings of the International Large Rivers Symposium: Canadian Journal of Fisheries and Aquatic Sciences, special publication 106.

Carr, J.E., Chase, Edith, Paulson, Richard, and Moody, David, 1987, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Cayan, D.R., Kammerdiener, S., Dettinger, M.D., Caprio, J.M., and Peterson, D.H., 2001, Changes in the onset of spring in the western United States: Bulletin of the American Meteorological Society 82, p. 399–415.

Cody, B.A., and Hughes, H.S., 2003, Water resource issues in the 108th Congress: Congressional Research Service Report to Congress, RS20569, updated January 9, 2003, accessed February 20, 2004, at *http://www.ncseonline.org/nle/crsreports/03Feb/RS20569.pdf*

Collier, Michael, Webb, R.H., and Schmidt, J.C., 1996, A primer on the downstream effects of dams: U.S. Geological Survey Circular 1126, 94 p.

Conover, W.J., 1980, Practical nonparametric statistics (2d ed.): New York, John Wiley & Sons, 493 p.

Cooperrider, A.Y., Wilcove, D.S., and contributors, 1995, Defending the desert-conserving biodiversity of BLM lands in the Southwest: New York, Environmental Defense Fund, 148 p.

Cordy, G.E., Duran, N.L., Bouwer, Herman, Rice, R.C., Furlong, E.T., Zaugg, S.D., Meyer, M.T., Barber, L.B., and Kolpin, D.W., Do pharmaceuticals, pathogens, and other organic wastewater compounds persist when wastewater is used for recharge?: Ground Water Monitoring and Remediation, v. 24, no. 2, p. 58–69.

Culler, R.C., and others, 1970, Objectives, methods, and environment—Gila River Phreatophyte Project, Graham County, Arizona: U.S. Geological Survey Professional Paper 655–A, 25 p.

Culler, R.C., Hanson, R.L., Myrick, R.M., Turner, R.M., and Kipple, F.P., 1982, Evapotranspiration before and after clearing phreatophytes, Gila River flood plain, Graham County, Arizona: U.S. Geological Survey Professional Paper 655–P, 52 p.

Daughton, C.G., and Ternes, T.A., 1999, Pharmaceuticals and personal care products in the environment—Agents of subtle change?: Environmental Health Perspectives, v. 107, Supplement 6, December 1999. URL *http://www.ameliaww.com/fpin/ProductsEnv.htm*

Dettinger, M.D., and Diaz, Henry, 2000, Global characterization of stream flow seasonality and variability: Journal of Hydrometeorology, v. 1, p. 289–310.

Dettinger, M.D., and Cayan, D.R., 1995, Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California: Journal of Climate, v. 8, no. 3, p. 606–623.

Dettinger, M.D., Cayan, D.R., Meyer, M.K., and Jeton, A.E., 2004, Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900–2099: Climatic Change, v. 62, no. 1, p. 283–317.

Edwards, B.D., and Evans, K.R., 2002, Saltwater intrusion in Los Angeles area coastal aquifers—The marine connection: U.S. Geological Survey Fact Sheet FS–030–02, 2 p.

Engberg, R.A., 1993, Effects of drainwater from irrigation projects on water quality, bottom sediment, and the biota, *in* Ecotoxicology and environmental chemistry—A global perspective: Libson, Portugal, Society of Environmental Toxicology and Chemistry, First SETAC World Congress, Abstract Book, March 28–31, 1993, p. 253–254.

Feth, J.H., and others, 1965, Preliminary map of the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million dissolved solids: U.S. Geological Survey Hydrologic Investigations Atlas HA–199, 31 p., 2 pls.

Focazio, M.J., Szabo, Zoltan, Kraemer, T.F., Mulin, A.H., Barringer, T.H., and DePaul, V.T., 2000, Occurrence of selected radionuclides in ground water used for drinking water in the United States—A targeted reconnaissance survey, 1998: U.S. Geological Survey Water-Resources Investigations Report 00–4273, 46 p. URL *http://water.usgs.gov/pubs/wri/wri004273/*

Fuhrer, G.J., and others, 1999, The quality of our nation's waters—Nutrients and pesticides: U.S. Geological Survey Circular 1225, 82 p. URL *http://water.usgs.gov/pubs/circ/circ1225/*

Galloway, D.L., Alley, W.M., Barlow, P.M., Reilly, T.E., and Tucci, Patrick, 2003, Evolving issues and practices in managing ground-water resources—Case studies on the role of science: U.S. Geological Survey Circular 1247, 81 p. URL *http://water.usgs.gov/pubs/circ/2003/circ1247/*

Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, 175 p. URL *http://water.usgs.gov/pubs/circ/circ1182/*

Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., 2000, Measuring land subsidence from space: U.S. Geological Survey Fact Sheet FS–051–00, 1 folded sheet (4 p.).

Gannett, Marshall, 2003, Upper Klamath basin ground-water study: U.S. Geological Survey, accessed August 4, 2003, at URL *http://oregon.usgs.gov/projs_dir/or180/klamgw.html/*

Gilbert, G.K., 1917, Hydraulic mining debris in the Sierra Nevada: U.S. Geological Survey Professional Paper 105, 154 p.

Gleick, Peter, and Adams, B.D., 2000, Water—The potential consequences of climate variability and change for the water resources of the United States, *in* The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change, 160 p., accessed August 4, 2003, at URL *http://pacinst.org/ncawater.pdf/*

Gleick, P.H., 1996, Basic water requirements for human activities—Meeting basin needs: Water International, v. 21, no. 2, p. 83–92.

Gleick, P.H., 2000, The world's water 2000–2001: The biennial report on freshwater resources: Washington, D.C., Island Press, 335 p.

Gleick, P.H., and Chalecki, E.L., 1999, The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin River basins: Journal of the American Water Resources Association, v. 35, no. 6, p. 1429–1441.

Glennon, R.J., 2002, Water follies—Groundwater pumping and the fate of America's fresh waters: Washington, D.C., Island Press, 304 p.

Glennon, R.J., and Maddock, Thomas, 1994, In search of subflow—Arizona's futile effort to separate groundwater from surface water: Arizona Law Review, v. 36, no. 3, p. 567.

Goodrich, D.C., Chehbouni, A., Goff, B., MacNish, B., Maddock, T., Moran, S., Shuttleworth, W.J., Williams, D.G., Watts, C., Hipps, L.H., Cooper, D.I., Schieldge, J., Kerr, Y.H., Arias, H., Kirkland, M., Carlos, R., Cayrol, P., Kepner, W., Jones, B., Avissar, R., Begue, A., Bonnefond, J.M., Boulet, G., Branan, B., Brunel, J.P., Chen, L.C., Clarke, T., Davis, M.R., DeBruin, H., Dedieu, G., Elguero, E., Eichinger, W.E., Everitt, J., Garatuza-Payan, J., Gempko, V.L., Gupta, H., Harlow, C., Hartogensis, O., Helfert, M., Holifield, C., Hymer, D., Kahle, A., Keefer, T., Krishnamoorthy, S., Lhomme, J.P., Lagouarde, J.P., Lo Seen, D., Luquet, D., Marsett, R., Monteny, B., Ni, W., Noubellon, Y., Pinker, R., Peters, C., Pool, D., Qi, J., Rambal, S., Rodriguez, J., Santiago, F., Sano, E., Schaeffer, S.M., Schulte, M., Scott, R., Shao, X., Snyder, K.A., Sorooshian, S., Unkrich, C.L., Whitaker, M., and Yuce, I., 2000, Preface paper to the Semi-Arid Land-Surface-Atmosphere Program special issue: Agricultural and Forest Meteorology, v. 105, p. 3–20.

Grauch, V.J.S., Rodriguez, B.D., and Deszcz-Pan, Maryla, 2002, How geophysical methods have been used to understand the subsurface, *in* Bartolino, J.R., and Cole, J.C., Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, p. 36–37.

Groisman, P.Y., Knight, R.W., and Karl, T.R., 2001, Heavy precipitation and high streamflow in the contiguous United States—Trends in the 20th century: Bulletin of the American Meteorological Society, v. 82, p. 219–246.

Groisman, P.Y., Ya, P., Bradley, R.S., and Sun, B., 1999, The relationship of cloud cover to near-surface temperature and humidity—Comparison of GCM simulations with empirical data: Journal of Climate, v. 13, p. 1858–1878.

Guldin, R.W., 1989, An analysis of the water situation in the United States: 1989–2040: U.S. Forest Service General Technical Report RM–177, 178 p.

H. John Heinz III Center for Science, Economics and the Environment, 2002, The state of the nation's ecosystems—Measuring the lands, waters, and living resources of the United States: Cambridge, United Kingdom, Cambridge University Press, 270 p., accessed August 4, 2003, at URL *http://www.heinzctr.org/ecosystems/report.html/*

Heath, R.C., 1989, Basic ground-water hydrology: U.S. Geological Survey Professional Paper 2220, 84 p.

Hem, J.D., 1985, Study and interpretations of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 264 p. URL *http://water.usgs.gov/pubs/wsp/wsp2254/*

Hester, D.J., and Feller, M.R., 2002, Landscape change modeling, *in* Bartolino, J.R., and Cole, J.C., Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, p. 20–21. URL *http://water.usgs.gov/pubs/circ/2002/circ1222/*

Heywood, C.E., Bartolino, J.R., and Galloway, D.L., 2002, Land subsidence and how it is being studied in the basin, *in* Bartolino, J.R., and Cole, J.C., Ground-water resources of the Middle Rio Grande basin, New Mexico: U.S. Geological Survey Circular 1222, p. 88–89. URL *http://water.usgs.gov/pubs/circ/2002/circ1222/*

Heywood, C.E., Galloway, D.L., and Stork, S.V., 2002, Ground displacements caused by aquifer-system water-level variations observed using interferometric synthetic aperture radar near Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02–4235, 18 p.

Hillhouse, J.W., Reichard, E.G., and Ponti, D.J., 2002, Probing the Los Angeles basin—Insights into ground-water resources and earthquake hazards: U.S. Geological Survey Fact Sheet FS–086–02, 2 p.

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

Intergovernmental Panel on Climate Change, 2001a, Climate change 2001—Summary for policy makers, A report of working group I of the Intergovernmental Panel on Climate Change, accessed August 4, 2003, at URL *http://www.ipcc.ch/pub/spm22-01.pdf/*

Intergovernmental Panel on Climate Change, 2001b, Climate change 2001—Working group I, The scientific basis, Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., and Xiaosu, D., eds.: London, Cambridge Press, 944 p., accessed August 4, 2003, at URL *http://www.grida.no/climate/ipcc_tar/wg1/005.htm*

Kareiva, Peter, Marvier, M., McClure, M., 2000, Recovery and management options for spring/summer chinook salmon in the Columbia River basin: Science, v. 290, p. 977–979.

Karl, T.R., and Knight, R.W., 1998, Secular trends of precipitation amount, frequency, and intensity in the United States: Bulletin of the American Meteorological Society, v. 79, no. 2, p. 231–241.

Kernodle, J.M., McAda, D.P., and Thorn, C.R., 1995, Simulation of ground-water flow in the Albuquerque Basin, central New Mexico, 1901–1994, with projections to 2020: U.S. Geological Survey Water-Resources Investigations Report 94–4251, 114 p. URL *http://pubs.er.usgs.gov/pubs/wri/wri944251*

King, Trude, V.V., ed., 1995, Environmental considerations of active and abandoned mine lands—Lessons from Summitville, Colorado: U.S. Geological Survey Bulletin 2220, 38 p. URL *http://pubs.er.usgs.gov/pubs/b/b2220*

Knowles, N., and Cayan, D.R., 2002, Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary: Geophysical Research Letters, v. 29, no. 18, p. 38–1—38–4.

Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B., and Buxton, H.T., 2002, Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000—A national reconnaissance: Environmental Science and Technology, v. 36, no. 6, p. 1202–1211.

Land, L.F., and Armstrong, C.A., 1985, A preliminary assessment of land-surface subsidence in the El Paso area, Texas: U.S. Geological Survey Water-Resources Investigations Report 85–4155, 96 p. URL *http://pubs.er.usgs.gov/pubs/wri/wri854155*

Land, Michael, Everett, R.R., and Crawford, S.M., 2002, Geologic, hydrologic, and water-quality data from multiple-well monitoring sites in the Central and West Coast basins, Los Angeles County, California, 1995–2000: U.S. Geological Survey Open-File Report 01–277, 28 p. URL *http://pubs.er.usgs.gov/pubs/ofr/ofr01277*

Leake, S.A., 1997, Land subsidence from ground-water pumping: U.S. Geological Survey Web page—Impact of climate change and land use in the Southwestern United States, Human impacts on the landscape, accessed August 4, 2003, at URL *http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/*

Lindgren, Waldemar, and Ransom, F.L., 1906, Geology and gold deposits of the Cripple Creek district, Colorado: U.S. Geological Survey Professional Paper 54, 516 p.

Lins, H.F., and Slack, J.R., in press, Seasonal and regional characteristics of U.S. streamflow trends: Physical Geography.

Lins, H.F., and Slack, J.R., 1999, Streamflow trends in the United States: Geophysical Research Letters, v. 26, p. 227–230. URL *http://water.usgs.gov/osw/special/streamflowtrends.html*

Lynch, D.D., Risley, J.C., 2003, Klamath River basin hydrologic conditions prior to the September 2002 die-off of salmon and steelhead: U.S. Geological Survey Water-Resources Investigations Report 03–4099, 17 p., accessed August 6, 2003, at URL *http://or.water.usgs.gov/pubs/WRIR03-4099/wri034099.pdf*

McAda, D.P., and Barroll, Peggy, 2002, Simulation of ground-water flow in the Middle Rio Grande Basin between Cochiti and San Acacia, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02–4200, 88 p., URL *http://nm.water.usgs.gov/publications/abstracts/wrir02-4200.pdf*

McCabe, G.L., and Wolock, D.M., 2002, A step increase in streamflow in the conterminous United States: Geophysical Research Letters, v. 29, no. 24, p. 2185.

McFaul, E.J., Mason, G.T., Jr., Ferguson, W.B., and Lipin, B.R., 2000, U.S. Geological Survey mineral databases—MRDS and MAS/MILS: U.S. Geological Survey Digital-Data Series DDS–52, 2 discs.

McGuire, V.L., 2001, Water level change in the High Plains aquifer, 1980 to 1999: U.S. Geological Survey Fact Sheet FS–029–01, 2 p.

McGuire, V.L., 2003, Water-level changes in the High Plains aquifer, predevelopment to 2001, 1999 to 2000, and 2000 to 2001: U.S. Geological Survey Fact Sheet FS–078–03, 4 p. URL *http://pubs.er.usgs.gov/pubs/fs/fs07803*

McGuire, V.L., and Sharpe, J.B., 1997, Water-level changes in the High Plains aquifer, 1980 to 1995: U.S. Geological Survey Fact Sheet FS–068–97, 4 p.

McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., and Verstraeten, I.M., 2003, Water in storage and approaches to ground-water management, High Plains aquifer, 2000: U.S. Geological Survey Circular 1243, 51 p.

Mac, M.J., Opler, P.A., Puckett Haecker, C.E., and Doran, P.D., 1998, Status and trends of the nation's biological resources, v. 1: Reston, Virginia, U.S. Geological Survey, p. 1–436.

Mac, M.J., Opler, P.A., Puckett Haecker, C.E., and Doran, P.D., 1998, Status and trends of the nation's biological resources, v. 2: Reston, Virginia, U.S. Geological Survey, p. 437–964.

McAda, D.P., 1996, Plan of study to quantify the hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system near Albuquerque, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 96–4006, 58 p.

Merideth, Robert, Liverman, Diana, Bales, Roger, Patterson, Mark, eds., 1998, Climate variability and change in the Southwest—Impacts, information needs, and issues for policymaking: Tucson, Arizona, Final report of the Southwest Regional Climate Change Symposium and Workshop, September 3–5, 1997, accessed August 4, 2003, at URL *http://gcrio.org/NationalAssessment/southwest/swclimatereport.pdf/*

Milly, P.C., Wehterald, R.T., Dunne, K.A., and Delworth, T.L., 2002, Increasing risk of great floods in a changing climate: Nature, v. 415, p. 514–517, accessed August 4, 2003, at URL *http://www.nature.com/cgi- taf/DynaPage.taf?file=/nature/journal/v415/n6871/full/415514a_fs.html&content_filetype=PDF/*

Naiman, R.J., Magnuson, J.J., McKnight, D.M., and Stanford, J.A., eds., 1995, The freshwater imperative—A research agenda: Washington, D.C., National Academies Press, 165 p.

National Academy of Sciences, 1977, Drinking water and health: Washington, D.C., National Academy Press, 948 p.

National Ground Water Association, 2003, The ground water supply and its use, accessed August 4, 2003, at URL *http://www.wellowner.org/agroundwater/gwsupplyanduse.shtml/*

National Marine Fisheries Service, 1997, Endangered and threatened species; interim rule governing take of the threatened southern Oregon/Northern California Coast Evolutionary Significant Unit (ESU) of Coho Salmon, 50 CFR Part 227, Federal Register, v. 62, no. 138, Friday, July 18, 1997, Rules and Regulations, accessed August 6, 2003, at URL *http://www.nwr.noaa.gov/reference/frn/1997/62FR38479.pdf*

National Marine Fisheries Service, 2001, Biological opinion—Ongoing Klamath Project operations: U.S. Department of Commerce, 63 p., accessed August 4, 2003, at URL *http://www.usbr.gov/mp/kbao/*

National Research Council, 1991a, Mitigation losses from land subsidence in the United States: Washington, D.C., National Academy Press, 68 p., accessed August 4, 2003, at URL *http://www.nap.edu/books/POD309/html/index.html/*

National Research Council, 1991b, Opportunities in the hydrologic sciences: Washington, D.C., National Academy Press, 348 p., accessed August 4, 2003, at URL *http://books.nap.edu/books/0309042445/html/index.html/*

National Research Council, Board of Environmental Studies and Toxicology, 2002, Scientific evaluation of biological opinions on endangered and threatened fishes in the Klamath River basin: Interim report, accessed August 4, 2003, at URL *http://www.nap.edu/bboks/0309083249/html/*

National Research Council, Commission on Geosciences, Environment and Resources, 2000, Investigating ground-water systems on regional and national scales: Washington, D.C., National Academies Press, 70 p., accessed August 4, 2003, at URL *http://www.nap.edu/books/0309071828/html/*

National Research Council, Water Science and Technology Board, 2001a, Envisioning the agenda for water researches research in the twenty-first century: Washington, D.C., National Academy Press, 62 p., accessed August 4, 2003, at URL *http://books.nap.edu/books/0309075661/html/*

National Research Council, 2001b, Grand Challenges in Environmental Sciences, National Academy Press, Washington, D.C., 96 p., accessed February 20, 2004, at URL *http://www.nap.edu/books/0309072549/html/*

National Research Council, Water Science and Technology Board, 2002, Estimating water use in the United States—A new paradigm for the national water-use information program: Washington, D.C., National Academies Press, 37 p., accessed August 4, 2003, at URL *http://books.nap.edu/books/0309084830/html/1.html/*

National Science Board, 2000, Science and engineering indicators—2000: Arlington, Virginia, National Science Foundation, NSB–00–01, accessed August 4, 2003, at URL *http://www.nsf.gov/sbe/srs/seind00/start/htm/*

Parker, J.T.C., and Pool, D.R., 1998, Use of microgravity to assess the effects of El Niño on ground-water storage in Southern Arizona: U.S. Geological Survey Fact Sheet FS–060–98, 1 sheet.

Patten, D.T., 1997, Sustainability of western riparian ecosystems, *in* Minckley, W.L., ed., Aquatic ecosystems symposium: Denver, Colorado, Western Water Policy Review Advisory Commission, National Technical Information Service, p. 17–31.

Perry, M.J., Mackun, P.J., 2001, Population change and distribution, 1990 to 2000, Census 2000 Brief, United States Census 2000, U.S. Department of Commerce, U.S. Census Bureau, Report Number C2KBR/01–2, accessed August 4, 2003, at URL *http://www.census.gov/prod/2001pubs/c2kbr01-2.pdf*

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybiades, 2001, Geochemical characterization of ground-water flow in parts of the Santa Fe Group aquifer system, Middle Rio Grande basin, New Mexico, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande basin study—Proceedings of the fourth annual workshop, Albuquerque, New Mexico, February 15–16, 2000: U.S. Geological Survey Open-File Report 00–488, p. 7–10.

Pohl, M., 2000, Constructing knowledge on American dam removal, *in* The future of dams and their reservoirs: Denver, Colorado, U.S. Society on Dams, p. 501–509.

Pool, D.R., and Eychaner, James, 1995, Measurements of aquifer-storage change and specific yield using gravity surveys: Ground Water, v. 33, no. 3, p. 425–432.

Pool, D.R., and Schmidt, Werner, 1997, Measurements of ground-water storage change and specific yield using the temporal gravity method near Rillito Creek, Tucson, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97–4125, 30 p.

Postel, S., and Richter, B.D., 2003, Rivers for life—Managing water for people and nature: Washington, D.C., Island Press, 253 p.

Powell, J.W., 1878, Report on the lands of the arid region of the United States, with a more detailed account of the lands of Utah: U.S. Congress, 45th, 2d session, House Executive Document, 195 p.

Reichard, E.G., Land, Michael, Crawford, S.M., Johnson, Tyler, Everett, R.R., Kulshan, T.V., Ponti, D.J., Halford, K.L., Johnson, T.A., Paybins, K.S., and Nishikawa, Tracy, 2003, Geohydrology, geochemistry, and ground-water simulation-optimization of the Central and West Coast basins, Los Angeles County, California: U.S. Geological Survey Water-Resources Investigations Report 03–4065, URL *http://pubs.er.usgs.gov/pubs/wri/wri034065*

Riebsame, W.E., ed., 1997, Atlas of the new West—Portrait of a changing region: New York, W.W. Norton and Company, 192 p.

Risley, J.C., and Laenen, Antonius, 1999, Upper Klamath Lake basin nutrient-loading study—Assessment of historic flows in the Williamson and Sprague Rivers: U.S. Geological Survey Water-Resources Investigations Report 98–4198, 28 p.

Robinson, T.W., 1965, Introduction, spread, and areal extent of saltcedar (*Tamarix*) in the western states: U.S. Geological Survey Professional Paper 491–A, 12 p.

Roos, M., 1991, A trend of decreasing snowmelt runoff in California: Juneau, Alaska, Proceedings, 59th Western Snow Conference, p. 29–36.

Ryker, S.J., 2001, Mapping arsenic in groundwater: Geotimes, v. 46, no. 11, p. 34–36.

Sax, J.L., Thompson, B.H., Leshy, J.D., Abrams, R.H., 2000, Legal control of water resources (3d ed.): St. Paul, Minnesota, American Casebook Series, West Group, 956 p.

Schmidt, J.C., Webb, R.H., Valdez, G., Marzolf, R., Stevens, L.E., 1998, Science and values in river restoration in the Grand Canyon: BioScience, v. 48. no. 9, p. 735–747.

Schroeder, R.A., and Anders, Robert, 2002, Transport and fate of water-quality indicators after 40 years of artificial recharge with treated municipal wastewater to the central ground-water basin in Los Angeles County, *in* Aiken, G.R., and Kuniansky, E.L., eds., U.S. Geological Survey Artificial Recharge Workshop Proceedings, Sacramento, California, April 2–4, 2002: U.S. Geological Survey Open-File Report 02–89, 92 p.

Scott, Russell, Goodrich, David, Stromberg, Julie, and Leenhouts, James, 2002, SPRNCA water needs study midyear progress report: USDA-Agricultural Research Service, 35 p.

Sedlak, D.L., Gray, J.L., and Pinkston, K.E., 2000, Understanding microcontaminants in recycled water: Environmental Science and Technology, v. 34, p. 509A–515A.

Shelton, J.L., Burow, K.R., Belitz, Kenneth, Dubrovsky, N.M., Land, Michael, and Gronberg, JoAnn, 2001, Low-level volatile organic compounds in active public supply wells as ground-water traces in the Los Angeles physiographic basin, California, 2000: U.S. Geological Survey Water-Resources Investigations Report 01–4188, 35 p. URL *http://pubs.er.usgs.gov/pubs/wri/wri014188*

Solley, W.B., Pierce, R.R., Perlman, H.A., 1998, Estimated water use in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p. URL *http://water.usgs.gov/watuse/pdf1995/html/*

Snyder, D.T., and Morace, J.L., 1997, Nitrogen and phosphorus loading from drained wetlands adjacent to Upper Klamath and Agency Lakes, Oregon: U.S. Geological Survey Water-Resources Investigations Report 97–4059, 67 p., 2 pls.

Stewart, I., Cayan, D.R., and Dettinger, M.D., 2004, Changes in snowmelt runoff timing in western North America under a “Business as Usual” climate change scenario: Climatic Change 62, p. 217–232.

Taylor, C.J., and Alley, W.M., 2001, Ground-water-level monitoring and the importance of long-term water-level data: U.S. Geological Survey Circular 1217, 68 p. URL *http://water.usgs.gov/pubs/circ/circ1217/*

Tiedeman, C.R., Kernodle, J.M., and McAda, D.P., 1998, Application of nonlinear-regression methods to a groundwater flow model of the Albuquerque basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 98–4172, 90 p.

Todd, D.K., 1959, Annotated bibliography on artificial recharge of ground water through 1954: U.S. Geological Survey Water-Supply Paper 1477, 115 p.

U.S. Bureau of Reclamation, 1995, Operation of Glen Canyon Dam, Colorado River Storage Project, Arizona—Final Environmental Impact Statement: 425 p.

U.S. Army Corps of Engineers, 2001, National inventory of dams, accessed August 4, 2003, at URL *http://crunch.tec.army.mil/nid/webpages/nid.cfm/*

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, 1990, 50 years of population change along the nation’s coast—1960–2010: Rockville, Maryland, 41 p.

U.S. Department of Commerce, 2000, National Marine Fisheries Service, Northwest Region, Endangered Species Act—Section 7 Consultation, Biological Opinion, Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin, December 21, 2000, accessed August 7, 2003, at URL *http://www.nwr.noaa.gov/1hydrop/hydroweb/docs/Final/2000Biop.html*

U.S. Department of Commerce, U.S. Census Bureau, 2001, Population change and distribution 1990 to 2000, Report Number C2kBR/01–2, accessed August 4, 2003, at URL *http://books.nap.edu/books/0309042445/html/index.html*

U.S. Department of the Interior, 2003, Water 2025—Preventing crises and conflict in the West: Department of the Interior, accessed February 20, 2004, at URL *http://www.doi.gov/water2025/Water2025.pdf*

U.S. Environmental Protection Agency, 2000, Estimated per capita water ingestion in the United States: EPA 822–R–00–008, April 2000, 50 p.

U.S. Environmental Protection Agency, 2001, Office of Ground Water and Drinking Water, National Primary Drinking Water Regulations: Arsenic and clarifications to compliance and new source contaminants monitoring; final rule, accessed August 7, 2003, at URL *http://www.epa.gov/safewater/ars/arsenic_finalrule.html*

U.S. Fish and Wildlife Service, 1988, Endangered and threatened wildlife and plants—Determination of endangered status for the Shortnose sucker and Lost River sucker: Federal Register, v. 53, no. 137, p. 27130–27134.

U.S. Fish and Wildlife Service, 1999, Endangered and threatened wildlife and plants; designation of critical habitat for the Huachuca water umbel, a plant: Federal Register, v. 64, no. 132, p. 37441–37453.

U.S. Fish and Wildlife Service, 2001, Biological conference opinion regarding the effects of operation of the Bureau of Reclamation's Klamath Project on the endangered Lost River sucker (*Deltistes lusatus*), endangered Shortnose sucker (*Chasmistes brevirostris*), threatened bald eagle (*Haliaeetus leucocephalus*), and proposed critical habitat for the Lost River/Shortnose suckers, Klamath Falls, Oregon: Oregon, Klamath Falls Fish and Wildlife Office, accessed August 4, 2003, at URL *http://klamathfallsfwo.fws.gov/*

U.S. General Accounting Office, 1996, Federal land management—Information efforts to inventory abandoned hard rock mines: Washington, D.C., GAO/RCED–96–30, 22 p.

U.S. Geological Survey, 1984, National water summary 1983—Hydrologic events and issues: U.S. Geological Survey Water-Supply Paper 2250, 243 p.

U.S. Geological Survey, 1998, Strategic directions for the U.S. Geological Survey Ground-Water Resources Program—A report to Congress, November 30, 1998, 14 p., accessed August 4, 2003, at URL *http://water.usgs.gov/ogw/gwrp/stratdir/stratdir.html/*

U.S. Geological Survey, and Sander Geophysics, Ltd., 1998, Digital data from the Isleta-Kirtland aeromagnetic survey, collected south of Albuquerque, New Mexico: U.S. Geological Survey Open-File Report 98–341, CD-ROM.

U.S. House of Representatives, Science Subcommittee, 1998, Unlocking our future—Toward a new national science policy: A report to Congress by the House Committee on Science, September 24, 1998, accessed August 4, 2003, at URL *http://www.house.gov/science/science_policy_report.htm/*

Waldman, Jon, 2002, The sod squad wants to soak you: High Country News, v. 34, Issue 15.

Warren, M.L., and Burr, B.M., 1994, Status of freshwater fishes of the United States—Overview of an imperiled fauna: Fisheries, v. 19, no. 1, p. 6–18.

Weeks, E.P., 2002, A historical overview of hydrologic studies of artificial recharge in the U.S. Geological Survey, *in* Aiken, G.R., and Kuniansky, E.L., eds., U.S. Geological Survey Artificial Recharge Workshop Proceedings, Sacramento, California, April 2–4, 2002: U.S. Geological Survey Open-File Report 02–89, 92 p.

Weeks, E.P., Weaver, H.L., Campbell, G.S., Tanner, B.D., 1987, Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico: U.S. Geological Survey Professional Paper 491–G, 33 p.

Welch, A.H., Watkins, S.H., Helsel, D.R., and Focazio, M.J., 2000, Arsenic in ground-water resources of the United States: U.S. Geological Survey Fact Sheet FS–063–00, 2 p., *URL http://co.water.usgs.gov/trace/pubs/fs-063-00/*

Welder, G.E., 1988, Hydrologic effects of phreatophyte control, Acme-Artesia reach of the Pecos River, New Mexico, 1967–82: U.S. Geological Survey Water-Resources Investigations Report 87–4148, 46 p.

Western Water Policy Review Advisory Commission, 1998, Water in the West—Challenge for the next century: Springfield, Virginia, National Technical Information Service, 443 p.

White, D.E., Baker, E.T., Jr., and Sperka, Roger, 1997, Hydrology of the shallow aquifer and uppermost semiconfined aquifer near El Paso, Texas: U.S. Geological Survey Water-Resources Investigations Report 97–4263, 37 p., 4 pl.

Wilbert, C.W., Pellegrino, John, Scott, Jennifer, Zhang, Qian, 1999, U.S. Bureau of Reclamation, Water treatment estimation routine (WaTER) user manual, 139 p., accessed August 4, 2003, at URL *http://www.usbr.gov/pmts/water/media/pdfs/report043.pdf/*

Williams, S.J., Dodd, Kurt, and Gohn, K.K., 1990, Coasts in crisis: U.S. Geological Survey Circular 1075, 32 p., URL *http://pubs.usgs.gov/circ/c1075/*

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water—A single resource: U.S. Geological Survey Circular 1139, 79 p., URL *http://water.usgs.gov/pubs/circ/circ1139/*

Wood, T.M., 1999, Sediment oxygen demand in Upper Klamath and Agency Lakes, Oregon: U.S. Geological Survey Water-Resources Investigations Report 01–4080, 19 p., URL *http://oregon.usgs.gov/pubs_dir/WRIR01-4080/wri014080.pdf/*

Wood, T.M., 2003, Movements and behavior of radio-tagged adult Lost River and Shortnose suckers in response to water quality in Upper Klamath Lake, Oregon, URL *http://oregon.usgs.gov/projs_dir/or207/*

Worster, Donald, 2001, A river running West—The life of John Wesley Powell: New York, Oxford Press, 673 p.

Zinn, J.A., 1997, Oceans and coastal resources—Coastal demographics and development patterns: Congressional Research Service Report 97–588 ENR, accessed August 4, 2003, at URL *http://www.ncseonline.org/nle/crsreports/briefingbooks/oceans/j.cfm/*

Appendix

World Wide Web Addresses for Water-Management Agencies in the Western States

Alaska	*http://www.dnr.state.ak.us/mlw/*
Arizona	*http://www.water.az.gov/*
California	*http://www.waterrights.ca.gov/*
Colorado	*http://water.state.co.us/*
Kansas	*http://www.kwo.org/*
Idaho	*http://www.idwr.state.id.us/*
Montana	*http://www.dnrc.state.mt.us/wrd/home.htm*
Nebraska	*http://www.dnr.state.ne.us/*
Nevada	*http://ndwr.state.nv.us/*
New Mexico	*http://www.ose.state.nm.us/index.html*
North Dakota	*http://www.swc.state.nd.us/*
Oklahoma	*http://www.owrb.state.ok.us/*
Oregon	*http://www.wrd.state.or.us/*
South Dakota	*http://www.state.sd.us/denr/denr.html*
Texas	*http://www.tceq.state.tx.us/*
Utah	*http://www.waterrights.utah.gov/*
Washington	*http://www.www.ecy.wa.gov/*
Wyoming	*http://seo.state.wy.us/*