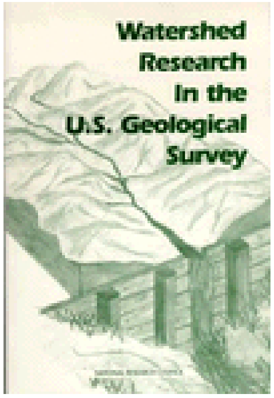

Watershed Research in the U.S. Geological Survey

Committee on U.S. Geological Survey, National Research Council

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Watershed Research in the U.S. Geological Survey

Committee on U.S. Geological Survey Water Resources Research
Water Science and Technology Board
Commission on Geosciences, Environment, and Resources

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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

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Cover art by Angela Brubaker. Angela is a research assistant with the Water Science and Technology Board staff. The sketch is intended to convey an image of the relationship between the "scales" of interest in hydrology, a characteristic that presents one of the great challenges to the science.

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Preface

This report is a product of the Committee on U.S. Geological Survey (USGS) Water Resources Research, which provides consensus advice to the Water Resources Division (WRD) of the USGS on scientific, research, and programmatic issues. The committee is one of the groups that works under the auspices of the Water Science and Technology Board of the National Research Council. The committee considers a variety of topics that are important scientifically and programmatically to the USGS and the nation and issues reports when appropriate.

This report concerns WRD watershed research activities. Within the USGS, this work is dispersed in a number of WRD program areas, including basic research, regional and site assessments, and data collection activities.

The work of the USGS in this area is important, as government agencies with natural resource management responsibilities are exploring the potential for program integration on a watershed basis. The interest in program integration and multiple-objective watershed management creates new demands for understanding of and information on hydrologic processes and related chemical, physical, and biological effects. Improvements in our understanding of the total ecosystem within a watershed, including the complex interrelationships among the various components, are needed.

This report addresses an overall framework for the agency's research in watershed systems while suggesting general areas of scientific opportunity, including communications and education. The report does not represent an in-depth review of all germane WRD watershed-related programs and projects but instead is intended to provide strategic advice to WRD management.

The committee began this project in November 1994, with briefings by USGS personnel and the selection of a set of questions to be addressed.

Subsequently, the committee met five more times before completing this report. At the meetings committee members were briefed by USGS personnel on a variety of watershed-related programs and visited USGS field sites at Panola Mountain, Georgia, and Luquillo Experiment Forest, Puerto Rico. Committee members drafted individual contributions and deliberated as a group to achieve consensus on the content of this report.

As the committee became more cognizant of USGS watershed-related activities, productive discussions occurred between committee members and USGS personnel. This interaction was critical to the success of the project. The committee is particularly grateful to Dr. Robert M. Hirsch, chief hydrologist, Dr. Harry F. Lins, WRD hydrologist, and their colleagues for all the information and cooperation they provided.

It is hoped that this report will convey the importance of understanding hydrologic processes in a watershed context and will lead to improvements in watershed and environmental management, consistent with society's broader goal of sustainable development. Successful work by the USGS in this area is very important to making progress in this critical aspect of hydrologic science.

George M. Hornberger, Chair

Committee on U.S. Geological Survey Water Resources Research

Contents

Executive Summary

Watershed research is conducted by the U.S. Geological Survey (USGS) to expand our understanding of basic hydrologic mechanisms and their responses at the watershed scale and to provide information that serves as the basis for water and environmental management activities carried out largely by other governmental and private entities. The work of the USGS in this area is carried out by its Water Resources Division and occurs in three general program areas: basic research, regional and site assessments, and data collection. These activities are becoming increasingly important, especially in the context of water and environmental management, where contemporary problems are being approached more than ever on an integrated ecosystems or watershed basis and where the underlying physical, chemical, and biological science is complex.

Although the value of this type of hydrologic research is well recognized within the USGS, available financial resources to support it remain modest. Thus, this study seeks to help maximize the effectiveness of the agency's work. The study took two years, during which time the committee visited field sites, received briefings, reviewed descriptive materials, deliberated toward conclusions, and wrote this report. Recommendations are intended to assist the USGS in improving its overall strategy for work in this area; descriptions of a number of scientific opportunities are included, and appropriate circumstances for collaboration with and support for others are identified.

The committee concluded that the needs for watershed science are considerable and diverse and that the USGS, as a scientific nonregulatory agency, has important roles to play in generating knowledge, information, and data. To be most effective, the USGS must focus most of its work in areas that can provide key information on problems of significance to the nation. The committee identified four particular research areas that merit more attention than in the past: (1) relatively larger watersheds, (2) urban and urbanizing watersheds, (3) restoration of damaged watersheds, and (4) erosion and sedimentation processes in watersheds. These conclusions follow from the finding that transferring knowledge about processes affecting the quantity and quality of water from work in small, relatively pristine watersheds to larger and/or more urban watersheds has not always been effectual. Although there is great interest and merit in restoration of aquatic ecosystems, the scientific basis supporting relevant decisions is weak. Further, renewed attention to the science of erosion and sediment transport and deposition is required to help address problems related to the transport and fate of sediment-bound hazardous materials in watershed systems.

An effective watershed research program for the USGS should consist of three main components: measurement and monitoring for a hierarchy of watersheds of various sizes; intense study of several small experimental watersheds to provide information on hydrologic processes for other major programs (e.g., the National Water Quality Assessment program); and a modeling program component to help interpret measurements made at the large scale in terms of process understanding occurring at the smaller scale.

The USGS already has in place much activity of this nature. However, there is not an adequate organizational structure to provide for integration of efforts. Such a structure should be established in order to develop important links among elements. Additionally, there needs to be a commitment to making advances in hydrologic modeling and the maintenance of any research watershed for at least 10 years; observations over lesser time periods are of little value.

Finally, there are many opportunities to collaborate on watershed work with others. The Agricultural Research Service, Forest Service, and National Science Foundation carry out or support watershed research similar in nature to that of the USGS. Collaboration, which is already occurring in a number of instances, can effectively expand the resources and experiences of all involved and should be pursued. Management or regulatory agencies, such as the Corps of Engineers, Bureau of Reclamation, Natural Resources Conservation Service, Environmental Protection Agency, and many state agencies, have strong interests in the results of watershed work. Coordination with such "consumers" can help contribute to better resource management and help assure continued relevancy of USGS efforts. The USGS also must look to the future and help educate properly the next generation of water resources professionals. Collaboration with university students, professors, and researchers on watershed projects represents an excellent opportunity and has many benefits—both to the USGS and to students—and must be pursued.

1

Introduction

The watershed, a physiographic area bounded by the drainage divide and within which precipitation drains to a point of interest, provides a fundamental spatial unit for hydrologic field observation and analysis. The U.S. Geological Survey (USGS) and other federal agencies undertake a wide range of activities related to the integrated analysis of phenomena occurring within watersheds. For several years the USGS has emphasized research on relatively small (generally less than 100 hectares), undisturbed watersheds to explore basic relationships in geochemical and biogeochemical cycles (Lins, 1994). This work has been quite effective in generating understanding of physical, chemical, and biological processes that affect the quantity and quality of waters in and issuing from small watersheds. In many instances fundamental research in small watersheds is justified simply because clear scientific understanding of certain processes is lacking. Contributions to fundamental knowledge are one important justification for maintaining a program of research on small, relatively undeveloped watersheds (Box 1.1).

The USGS also has recognized that there are many problems facing the nation that involve watersheds of large areal extent and watersheds in which land-use changes have substantially altered water flows and the transport of chemicals and sediments relative to pristine conditions. Efforts also are increasing to restore the hydrologic functioning of altered watersheds, and little is known about the effectiveness of restoration schemes. There is a serious need for a coordinated, long-term research effort to develop the knowledge base needed to deal with water resources issues on large and impacted watersheds. An effective program will require coordination of broad data collection activities, intensive research at small scales, and construction and verification of models of larger-scale watersheds. The USGS, as the lead federal geosciences agency responsible for assessing water resources, should support a set of activities in watershed science that focuses

BOX 1.1 HUBBARD BROOK: A LABORATORY FOR INTERDISCIPLINARY ECOSYSTEM-LEVEL RESEARCH

The Hubbard Brook Experimental Forest (HBEF) was established in 1955 by the U.S. Forest Service as a center for hydrologic research in New England. In 1963 the research focus at the site was expanded, through a cooperative agreement between researchers at the U. S. Forest Service and Dartmouth College, to use the small watershed approach to study element cycling. During the intervening years the scope of research at the HBEF has continued to evolve through the interests of scientists, as well as in response to regional and national environmental issues. Today Hubbard Brook is a site for comprehensive ecosystem-level research (the Hubbard Brook Ecosystem Study, HBES) and involves cooperation among the U.S. Forest Service, the Institute of Ecosystems Studies of the New York Botanical Garden, numerous universities (Cornell, Dartmouth, Syracuse, Yale, New Hampshire, Pennsylvania, Wyoming, SUNY College of Environmental Science and Forestry), the Ecosystem Center of the Marine Biological Laboratory in Woods Hole, the U.S. Soil Conservation Service, and the U.S. Geological Survey. The National Science Foundation has been a major source of financial support for HBES for the past 34 years. The work has resulted in about 1,000 publications.

The HBEF is a 3176-ha, bowl-shaped area within the boundaries of the White Mountain National Forest, New Hampshire. It has hilly terrain, ranging from 222 to 1015 m in altitude and except for some experimental areas is covered by unbroken forest of northern hard-woods with spruce and fir at higher elevations. Other salient features include relatively impermeable bedrock; well-defined watershed boundaries; reasonably homogeneous geological features, soil types, vegetation, and climate; year-round precipitation and streamflow; absence of major forest disturbance for about 85 years; and several clusters of similar-sized catchments where entire watersheds can be treated experimentally and compared. The presence of Mirror Lake in the Hubbard Brook Valley has provided a unique opportunity to investigate and quantify land-water interactions. Whole ecosystem manipulations include a variety of forest clearcut studies on experimental watersheds, stream chemical manipulation studies, and lake tracer experiments.

> With careful measurements of precipitation input and stream outflow, accurate water and element balances can be constructed. A continous database has existed since 1956 for streamflow, precipitation, and other meteorological observations for eight experimental watersheds. Measurements of precipitation and streamwater chemistry have been ongoing since 1963. The long-term record at Hubbard Brook provides (1) insight into ecosystem function; (2) empirical data for testing models and generating hypotheses; (3) a record of extreme or unusual events; and (4) information that is relevant to regional, national, and global issues. Hubbard Brook is truly a site of interdisciplinary ecosystem-level research where there is close cooperation among biological, chemical, and physical scientists.

on assessing and understanding trends in geological, hydrologic, biological, demographic, and land-use patterns that will produce the knowledge base for addressing critical problems.

In its Strategic Plan the USGS states a series of general goals for the agency for the next decade (USGS, 1996a). The plan recognizes that studies of water resources will remain a key activity of the agency and that reliance on the combination of three efforts—data collection, interpretative studies, and research—will continue. The plan points out that "as population increases and relocates, the overall level of water monitoring will increase in areas of high urban and agricultural water use, but it may decrease in other areas" (USGS, 1996a). These shifts may affect all three of the USGS efforts in watershed science, interpretative studies, and research, as well as data collection.

Another facet of change that has potential impact on watershed activities of the USGS is the very recent creation of the Biological Resources Division (BRD). The BRD brings new capabilities to the USGS for assessing aquatic biological resources (USGS, 1996b). Organization of efforts for building the knowledge base to solve interdisciplinary problems may be enhanced substantially through collaborations between the Water Resources Division and the BRD.

Given the importance of watershed science for addressing a host of current water-resources issues, this assessment focused on the goals and design for the watershed research effort within the USGS and sought to address the following questions:

- What should be the underlying strategy for USGS watershed research activities? What are the key design elements for an effective program in watershed science?
- What are the major opportunities for advances in the USGS's capability in watershed science?
- How should activities in water research support ongoing USGS programs, especially NAWQA (National Water Quality Assessment program) and the long-term observing networks, and vice versa?
- What should be the appropriate links with programs in watershed research and management in other agencies and institutions?
- What are the appropriate internal USGS links, given the broad array of watershed-related research going on within the agency?
- What are the implementation requirements for effective operation of watershed research activities to address important management issues?

The remainder of this report contains the analyses, conclusions, and recommendations of the committee. We provide the context for watershed activities in the USGS, that is, the need to address issues related to watershed management. The historical background for work on research watersheds is summarized, and current efforts by a number of federal agencies are discussed. With this background, the report presents a view of important focus areas for watershed research and views on key program areas to which the USGS might orient major activities to provide the necessary knowledge base for addressing critical watershed issues. The final chapter contains conclusions and recommendations that stem from the discussions, deliberations, and analyses of the committee.

2

Watershed Research for Water Management

Watershed research in the U.S. Geological Survey (USGS) is guided not only by the need to expand basic knowledge of watershed processes but also by the needs of other public and private organizations for a better scientific basis for design and implementation of management programs. Among public agencies that depend on the USGS and other endeavors in watershed research are management programs at the federal level, including the Natural Resources Conservation Service (NRCS), Army Corps of Engineers (COE), Bureau of Reclamation (BuRec), Forest Service, Environmental Protection Agency (EPA), Fish and Wildlife Service, and National Weather Service. At the state level are water quality management and other natural resources agencies. Local governments are particularly active in management of watersheds that serve as public water supplies and in management of stormwater from urban watersheds. Many private-sector endeavors also are dependent upon knowledge gained from watershed research, including privately owned water supply and electric power utilities, forest products companies, and other manufacturing industries. The information needs of those users are many, and an appreciation for the nature of watershed activities undertaken by those organizations is important to USGS as it pursues its research endeavors.

WATERSHEDS IN RESOURCE MANAGEMENT

Origins

Use of watersheds or river basins as the fundamental spatial unit for analysis is one of the earliest principles to evolve from American policies for planning and managing water resources. Its roots reach to the middle of the nineteenth century when debate began on alternative strategies for managing floods along the Mississippi River, whether the policy should be one of building levees alone in the vicinity of properties exposed to risk or one of levees in combination with reservoirs in headwater streams. It was also at the core of much of the nation's early earth science research, as characterized particularly by the Colorado expeditions of John Wesley Powell, second director of the U.S. Geological Survey.

The concept of watershed management was elevated during the conservation movement in the early twentieth century through the work of several commissions during the presidency of Theodore Roosevelt. W.J. McGee, one of several influential leaders in the administration, wrote in an article in 1907 that each stream is an interrelated system in which control of any part will affect, to some extent, every other part.

Watersheds became a cornerstone of planning practice beginning in the 1920s as federal agencies, including COE, BuRec, Tennessee Valley Authority, and the Soil Conservation Service (SCS) began planning for development of the nation's waterways. That concept was central to much of the public and private development to improve navigation, control flooding, and develop rivers for hydroelectric power, water supplies, and recreation, activities that reached a peak in the mid-1960s. For much of that period the emphasis in watershed research was on enhancing knowledge about quantities of water and its movement in streams, floodways, and reservoirs.

Some problems addressed by those planning activities remain national priorities today. Paramount among them is flood damage. Devastating floods in the Upper Mississippi Basin in 1993 were directly responsible for the loss of 38 lives and fiscal damage estimated to be in the range of $12 billion to $16 billion (Administration Floodplain Management Task Force, 1994). In the 1980s, average annual flood damages were approximately $4 billion in 1985 dollars (Federal Interagency Floodplain Management Task Force, 1992).

Erosion and Sedimentation

Perhaps the largest national program of watershed management is overseen by the NRCS. Concerns about erosion and sedimentation reached the status of a national priority in the early 1930s, leading to establishment of the SCS in 1933. Among its first initiatives was a set of demonstration projects that proved soil conservation and water conservation were inextricably linked. For the first 20 years of that program, conservation measures were limited to land treatment and minor structures for land stabilization. By the late 1940s, however, a substantial lobby had developed for structural measures in upland areas, and that pressure culminated in the passage of the Watershed Protection and Flood Prevention Act of 1954, also known as P.L. 566. This law provided 100 percent federal funding for flood control structures and 50 percent federal funding for other project purposes, including wildlife and recreation.

Agriculture development of forested lands has dramatically increased sediment yields in basins such as the Cayaguás in Puerto Rico. In this case, the sediment has been deposited in the principal water supply reservoir for the city of San Juan, Puerto Rico, causing a 60 percent reduction in its storage capacity since impoundment in 1954.
Source: U.S. Geological Survey.

With those incentives, SCS broadened its agenda, becoming a significant force in a wide variety of project purposes. Since 1954, the SCS (now called the Natural Resources Conservation Service) has initiated nearly 1,600 watershed projects, among which over 300 that started since 1975 are still active. Watersheds on which those projects are located have an average drainage area of about 360 square kilometers.

The purposes served by these projects have changed significantly since passage of the Water Resources Development Act of 1986. Changes in cost-sharing formulas in that act shifted a much greater burden of the financing to local sponsors, bringing about substantial reductions in the percentage of projects used for flood control and drainage, for recreation, and for municipal and industrial water supplies (Figure 2.1). Since 1986, a significantly higher percentage of projects have been used for watershed protection purposes that include erosion control and water quality improvements. Changes in that direction are consistent with NRCS's intent of moving toward "ecosystem-based integrated resource planning and management." Strategic plans for the NRCS include a Water Management Action Plan that envisions the agency providing assistance for integrated resource planning and management on a watershed basis (SCS, 1993, 1994).

Water Pollution Control

Watersheds also were adopted as basic units for managing environmental aspects of water resources, particularly the control of water pollution. A number of states adopted watershed programs for pollution control in the 1930s and 1940s. Federal- state cooperative efforts in the Scioto and Illinois rivers resulted in one of the first water pollution control surveys for an entire watershed. A study authorized by Congress in 1938 of the Ohio River and published as House Document No. 266 in 1944 became a landmark for pollution aspects of watershed management. By 1951, states and the U.S. Public Health Service had prepared initial reports for all major watersheds in the country (Dworsky, 1971). When federal policy emerged in the 1950s and 1960s, the use of watersheds in developing management programs became even more widespread. Experience from some of the better state programs was incorporated into guidance by the Federal Water Pollution Control Administration, encouraging states to use watersheds and river basins as spatial units for development of implementation plans required by amendments to the Federal Water Pollution Control Act in 1965. With these developments, research needs were expanded to focus added attention on the fate and transport of pollutants in streams.

Amendments to the Federal Water Pollution Control Act in 1972 brought about a number of fundamental changes in pollution policy in the United States, several of which were dependent heavily on watershed management. Section 303(e) of the act required each state to prepare plans to achieve water quality standards for each watershed in the state, taking into account nonpoint sources of pollution from urban, agricultural, silvicultural, and mining activities as well as point sources of municipal and industrial pollution. Inclusion of nonpoint sources, widely distributed over the landscape and transported by stormwater runoff, increased the importance of watershed processes in pollution control strategies. Section 208 of the act established areawide planning to embrace all municipal, industrial, and nonpoint sources of pollution in watersheds, particularly in metropolitan areas and other regions where point source controls alone were insufficient to satisfy water quality standards. Slow progress toward control of nonpoint sources led to inclusion of Section 319 in reauthorization of the Clean Water Act in 1987. That program established grants to states for reducing nonpoint source pollution on a watershed basis. Although it was initiated prior to 1987, the Chesapeake Bay Program, described in Box 2.1, provides a good example of efforts to manage a complex watershed in which both point and

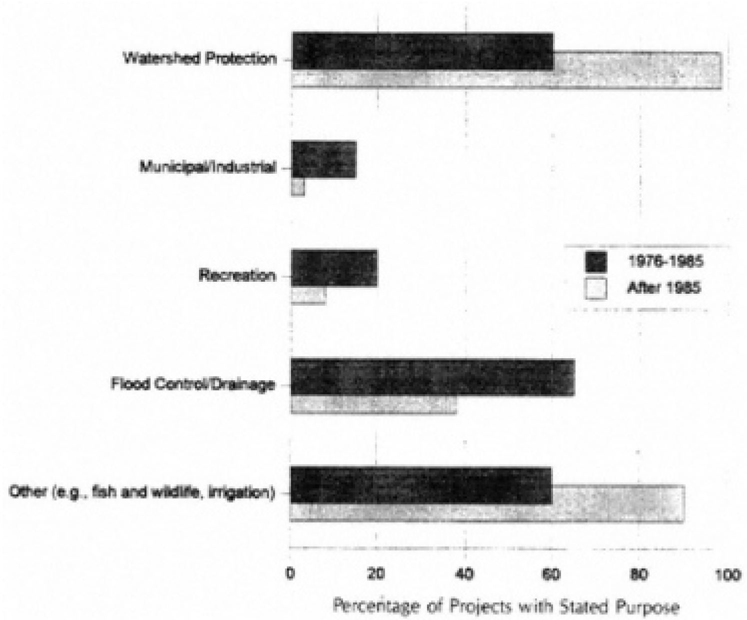

FIGURE 2.1 NRCS watershed projects by purposes: 1976–1985 and after 1985. Source: NRCS (1996).

BOX 2.1 CHESAPEAKE BAY PROGRAM

Chesapeake Bay is the largest estuary in the eastern United States with a drainage area of over 165,000 square kilometers, including portions of six states and the District of Columbia. Its highly productive ecosystem provides a rich abundance of fish and shellfish. Its vast area of open waters and surrounding wetlands and forests constitutes an enormous habitat for waterfowl and wildlife. Those same areas constitute a huge recreational resource. But the quality of these resources has been severely damaged from the cumulative effects of population growth (nearly 15 million in 1990), urbanization, industrialization, and intensive agricultural production within watersheds that drain to the bay. Watersheds of the Susquehanna, Potomac, and James rivers, ranging from 650 to 725 kilometers in length, have become highly developed, with over 40 percent of all lands in urban, suburban, or agricultural uses. Land has been developed at much greater intensity near the bay.

The bay is now the object of a major cleanup and restoration program involving all levels of government with widespread public participation. Among the highest-priority problems to be addressed are nutrient enrichment, loss of submerged aquatic vegetation (SAV), and toxics. Nutrient enrichment, particularly excessive nitrogen loads, have led to high levels of algal mass and indirectly to low levels of dissolved oxygen. SAV is an important component of the ecosystem, providing food and shelter for fish, finfish, waterfowl, and other aquatic resources. It also serves to filter and trap sediments and nutrients. Stresses imposed by toxics and losses of suitable habitat have led to suboptimal densities of zooplankton and degraded benthic conditions, leading to serious losses of fisheries of commercial and recreational importance. Particularly hard hit have been stocks of striped bass, shad, and oysters.

Efforts to formulate management plans for the bay have been under way for over 30 years. In 1965 the COE was directed to examine a broad array of water resource issues regarding the bay. With passage of Public Law 94-116 in 1975, a more intensive five- year, $27 million examination of water quality problems and their solution was initiated by the EPA. That program became known as the Chesapeake Bay Program (CBP). After 20 years of effort, the CBP has forged a working partnership with the states, and that partnership has formulated a series of tributary management strategies to address nitrogen and toxic loads. Key elements in those strategies are use of the best management practices for agriculture and urban stormwater runoff and reductions in loads from municipal and industrial sources.

information is needed from the research community on processes such as deposition, resuspension, transport, and fate of substances from a wide range of land types and uses.

Urban Stormwater

Among the earliest nuisances of urbanization that confronted local governments were problems of flooding, traffic disruption, and other adverse effects of excessive runoff from storm events. Many communities responded by developing watershed-wide stormwater management plans. In the 1960s, it became evident that urban stormwater also was having adverse effects on water quality in receiving streams, a special problem being that of combined sewer overflows. Since then, federal policymakers have struggled to find appropriate strategies for reducing those impacts. Until 1987, actions called for in the Clean Water Act were ignored because of the large costs to manage these sources. Amendments in 1987 established a timetable for large urban areas and industrial sites to obtain permits and adopt applicable standards for stormwater discharges.

More progressive communities have sought to integrate stormwater management in more comprehensive treatment of urban streams and related floodways. One such effort is that undertaken by the Denver metropolitan area, highlighted in Box 2.2. Among the scientific uncertainties confronted by these initiatives are (1) the transport and fate of nutrients, toxics, and sediments in the urban environment; (2) changes in low flows resulting from modifications to the watershed; and (3) responses of fish and aquatic ecosystems to changes in pollutant loads and habitat conditions, including vegetative cover and substrate.

BOX 2.2 SOUTH PLATTE RIVER INITIATIVES

Watersheds of the South Platte River in general and more specifically those in the Denver metropolitan area are the focus of several intensive investigations and planning efforts. The river, with its headwaters at the Continental Divide, winds it way along a 725-kilometer route to its confluence with the North Platte River in Nebraska, draining an area of 63,000 square kilometers in parts of three states, home to 2.4 million people. Denver draws its water supply from watersheds of the Upper South Platte; the river and its tributaries are significant urban amenities; those streams carry the runoff from periodic storm events; and the river receives effluent from the Metro Wastewater Reclamation District. The impacts of those uses are apparent in the upper and middle reaches of the river. Downstream reaches are more heavily influenced by agricultural runoff.

Twenty years ago the river, as it flowed through Denver, was described as a miserable, flood-ridden sewerway filled with the rubble of construction projects, discarded tires, other solid waste, and waste oil. That was before its potential as a valuable asset to the urban area was recognized.

Progress had been made by the early 1990s to establish a green-way system along the river, but more was needed to transform the river and related lands to resources that could be used for a variety of recreational purposes. One initiative taken by local officials, called Imperative 2000, created a vision for the South Platte that would further enhance the river and its corridor as a meeting place for people, as a place for plants and animals to flourish, and as a learning center. Efforts are under way to achieve those goals while continuing to use the river as a public water supply and a conveyance for flood waters. Proposed actions include alteration of magnitudes and timing of flows to meet instream needs, development of a coordinated approach to water quality management, enhancement of natural features of the corridors for recreational and ecological purposes, multiple-purpose utilization of upstream lands for flood reduction and open space, and provision of native species of trees and shrubs to improve vegetative cover for fish and wildlife.

Other initiatives are also under way. The U.S. Forest Service is considering designation of portions of the river above Denver as either a wild and scenic river or an alternative that would protect the river without formal designation. The state of Colorado, working with the EPA and local governments, is taking steps to formulate waste load allocations and total maximum daily loads for the river.

The USGS, has been a significant partner in the array of public and private organizations actively involved in understanding the science of the river. In 1991 the USGS undertook water quality investigations in the South Platte as part of the NAWQA program. Through that effort and a larger effort for the entire Platte River watershed, the USGS is investigating a variety of water quality problems, particularly those related to suspended sediment, pesticides, nutrients, and stream ecology.

Public Water Supplies

Many local governments also have relied on watershed management to protect their public water supplies. A study of threats posed by urban development to those watersheds and steps taken by local governments to protect them was undertaken by Burby et al. (1983), and a more recent survey of selected local government management programs was published by the American Water Works Association Research Foundation (Robbins et al., 1991).

Added attention was drawn to water supply watersheds when EPA adopted its Surface Water Treatment Rule in June 1989, using its authority under amendments to the Safe Drinking Water Act of 1986. That rule, which developed over several years after much public debate, places a number of restrictions on systems that do not use filtration to treat waters taken from surface sources, including several large systems such as those serving New York, Boston, and Seattle. In addition to many other requirements, systems not using filtration must manage their watersheds to minimize the potential for contamination by specific biological organisms. They must monitor and control activities in watersheds that could be sources of specified organisms, and they must demonstrate the capability to control human activities that could adversely affect water quality.

Watersheds as a Planning Framework

In addition to the role of watersheds in particular management contexts, watersheds have become a popular organizing framework for water resource planning in the 1990s. Policy advocates such as Water Quality 2000, a coalition of more than 80 organizations representing a variety of interest groups, have recommended that reauthorization of the Clean Water Act should reorient water resource programs and institutions along watershed boundaries. The Association of Metropolitan Sewerage Agencies has argued for a national program of comprehensive watershed management. In 1991 the EPA developed a "watershed protection approach" for its water quality management programs. A recent book, *Entering the Watershed*, (Doppelt et at., 1993) makes strong arguments for a comprehensive ecosystem-based watershed protection program.

EPA's (1991a) framework document for its watershed protection program sets forth the following goals: (1) to encourage state and local governments to target watersheds based on overall human health and ecological risk; (2) to develop site-specific integrated approaches to manage pollution; (3) to establish cooperative decisionmaking processes; and (4) to establish mechanisms for monitoring and evaluation. In March 1994, EPA formulated a statement that management of the resource should be adapted to the needs of particular locations. Subsequently, the agency established a Watershed Management Policy Committee to foster a watershed approach to environmental protection.

To implement this program, EPA identified a number of case studies through which methods would be developed. The initial list included 34 projects, ranging in size from a 50-square-kilometer watershed and bay on Cape Cod to a regional project in the Lower Mississippi Valley that covers 219 counties in portions of seven states. Among the most common of problems and threats identified in those watersheds were excessive nutrients and agricultural operations. Sedimentation was cited frequently, as were past mining activities.

The Chesapeake Bay, Great Lakes, and National Estuary programs are other instances where watershed approaches have been taken to restore significant large-scale ecosystems. Considerable attention has been fixed on the problem of identifying sources and predicting the transport and fate of excessive nutrient loads in tributary watersheds, including atmospheric nitrogen deposition. Potential leakage from hazardous waste facilities within these basins also has been estimated, and potential sources and fates of bioaccumulative pesticides have been identified.

In addition to its support for the case studies, EPA is tracking how states are adapting their water quality management programs to the Watershed Protection Approach. Specific components being tracked are (EPA, 1994):

- the wastewater discharge permit program,
- monitoring and assessment of water quality,
- management of nonpoint sources,
- ground water management, and
- establishment of total maximum daily loads and waste load allocation.

One of the programs that has been highlighted by EPA (1991b) is a "whole-basin" approach devised by North Carolina's Division of Environmental Management. Key elements of this program are to coordinate basin-wide water quality planning with issuance of discharge permits and to integrate management of point and nonpoint sources. Plans for the state's 17 river basins are scheduled to be updated on a staggered five-year cycle, and all discharge permits within each basin are to be reissued when plans are revised.

IMPLICATIONS FOR RESEARCH

Several elements of watershed management have emerged as being especially important and difficult as priorities have been established on nonpoint sources, pathogenic organisms, hazardous substances, wetlands protection, and ecosystem restoration. Many of those difficulties arise as planners try to apply information obtained at the small scale to formulate and evaluate programs for large-scale watersheds. Much of what is known about watershed management has been gained from work at small scales, and management programs are likely to be implemented at small scales—at the level of farms or even fields, subdivisions, commercial developments, and management of other types of activities. Among the difficult problems is predicting how large-scale ecosystems respond to many small-scale management practices, some of which may be rather distant from locations at which responses will be measured. Because interactions between sources of problems and responses may occur over long distances, an understanding of the transport and fate of chemicals and their impacts on biological organisms is essential to the development of sound management policies. Some pathways through which those materials travel involve interactions between surface water and ground water and between the surface and the atmosphere.

Incorporation of ecological systems into watershed management brings its own special set of challenges. While strategies call for integrated, holistic, ecosystem-based management, achieving that goal is far more difficult. Responses of ecosystems to management practices have been notoriously difficult to predict at the level of certainty often demanded in policymaking processes, many of which are being directed at causes rooted in land use and land management practices. Improvements in knowledge about watershed processes should lead to better-informed policies regarding land management.

3

Scientific Rationale for Watershed Research

WATERSHEDS AS ENVIRONMENTAL LABORATORIES

The goal of hydrologic science is to understand and predict the fluxes and storages of water over a range of space and time scales. Such understanding also is necessary to comprehend and predict fluxes and storages of sediments and solutes and to evaluate the suitability of the aquatic environment for living organisms. Experimentation is an essential part of science; in order to understand a phenomenon, it must be measured. Although many individual components of the hydrologic cycle (e.g., free-surface flow, porous media flow, evaporation, chemical transport) can be studied in the laboratory under carefully controlled conditions, the partitioning of rainfall into interception, infiltration, direct surface runoff, evaporation, and ground water recharge, taking into account the natural temporal and spatial variability of rainfall and soil and vegetative characteristics, can be observed in a meaningful way only at the watershed scale.

Scientists and laypersons alike are usually quite comfortable with the notion of laboratory research, but watershed research often has been viewed as collecting data for data's sake, with little scientific content. The major difference between watershed research and typical laboratory research involves the factors of complexity and control. A research or experimental watershed can be viewed as a special type of iconic "material model," just as a soil column in an indoor laboratory is a material model. To be sure, a watershed is much more complicated than a laboratory column, but it has many of the attributes required of material models. In general, a material model should be similar to but simpler than the prototype system and should provide the scientist with better control of the system and allow accurate measurements of inputs and outputs.

Carefully chosen research watersheds certainly can be simpler than some generic watersheds. For example, watersheds can be chosen such that there is little or no surface runoff or little or no subsurface runoff. In addition, the instrumentation provided in the research watershed provides the scientist with data that would be impossible to obtain without it. Just as the laboratory scientist is not interested in the data from a soil column per se, but is interested in how these data can be used to provide insight into the physical, chemical, or biological processes involved in a general system, the watershed scientist is not specifically interested in data from the watershed as would be the case for a monitoring activity. Both are interested in using the data obtained to improve intellectual or mathematical models and to estimate or provide techniques for field estimation of model parameters for a general system. The most significant deficiency of a watershed as a laboratory is that it is impossible to design, control, and replicate inputs. Nevertheless, information gained from work on research watersheds is one of the keys to developing a comprehensive predictive watershed science that can be applied to solve water resource problems. The "iconic" experimental watershed models are necessary to develop, test, and refine the mathematical models that are required to generalize results from site-specific studies and ultimately to allow the U.S. Geological Survey (USGS) to provide the tools for solving important problems on watersheds outside a research watershed network and on watersheds influenced by human activity.

HYDROLOGIC MODELS

Rosenblueth and Wiener (1945) defined two classes of models: (1) formal or intellectual and (2) material. The formal models generally consist of mathematical descriptions of real-world phenomena, whereas material models, including iconic or "look-alike" and analog models, are real systems that either closely resemble the prototype or have the same mathematical representations. In contemporary hydrology the most commonly utilized models belong to the class of formal or intellectual models. Models are an essential part of scientific inquiry and engineering practice. They can serve as a platform and repository for integrating new scientific knowledge and process understanding as it is developed. They help to identify and guide data needs for problem evaluation. A coordinated program of model development, laboratory work, and field data collection can accomplish far more than any of these activities alone. Models, properly verified and confirmed with field data, can provide an effective basis for evaluation of alternative management strategies and decision support.

Most hydrologic models consist of sets of linked ordinary or partial differential equations expressing various conservation laws along with appropriate initial and boundary conditions that must be consistent with the mathematical equations and system geometry. In most cases it is impossible to obtain analytical solutions to the sets of equations, so they are numerically solved on digital computers. To obtain numerical solutions, the continuous solution domain of the problem (which may include up to three space dimensions and time) is replaced by a grid function, and the solution to finite difference equations or finite element approximations is sought at this finite number of points. Several assumptions and approximations are required to formulate digital hydrologic models. First, a decision must be made regarding the scope (space and time) of the model and the variables to be considered. Second, decisions must be made regarding the physical principles or laws to be included. For example, most models include the principle of conservation of mass, some include conservation of momentum, and some include conservation of energy. Then equations are derived that reflect these principles and that also include certain empirical relationships such as Darcy's Law or Manning's equation. At this stage, many assumptions typically are introduced. For examples, rainfall rate is assumed to be a continuous input variable in space and time rather than consisting of discrete drops, watershed surfaces are assumed to be homogeneous, and the soil is assumed to be a homogeneous porous medium. Initial and boundary conditions consistent with the scope of the problem and with meeting the mathematical requirements of the sets of equations must then be specified. Finally, the grid or mesh structure must be specified and the appropriate equations solved.

Hydrologic models often are classified as lumped or distributed. In a lumped model the spatial independent variables are eliminated by assuming spatial or volumetric averages of dependent variables and parameters. Thus, lumped models consist of sets of ordinary differential equations. Distributed models, on the other hand, retain spatial variables, so they consist of linked partial differential equations. In most cases the distributed models are simplified by eliminating one or two spatial dimensions, which may introduce serious distortions.

A significant problem associated with hydrologic modeling is that of spatial variability of inputs, parameters, and variables at length scales smaller than the computational length scale. The seriousness of this problem is dependent on the scale of the system being modeled and the scale of variability relative to the computational scale. A valid research question that can only be answered with a combination of experimental watershed data and mathematical models is: "Can procedures developed to scale up from a watershed of 0.1 square kilometers to one of 10 square kilometers give insight into techniques required to scale up from 10 square kilometers to 100 square kilometers or greater?" A second problem that is particularly important in modeling the transport and fate of chemical constituents is that of specifying the initial conditions. For example, a model for nitrate transport through an agricultural watershed quickly "forgets" the initial conditions with respect to water stored in the soil, but the quantity, position, and chemical form (e.g., organic or inorganic) of nitrogen may be extremely important in attempting to evaluate the effect of changed agricultural practices on nitrate concentration and fluxes in the saturated zone.

For effective use in policy analysis, strategy selection, or engineering design, hydrologic models must be firmly founded on a strong base of observational data. Such data are essential to ensure that the model theory and structure are consistent with real-world behavior as well as conditions at the specific site where the model is applied. Observational data also are essential to test and confirm the predictive capability of the model for its intended application.

A BRIEF HISTORY OF WATERSHED RESEARCH

The importance and necessity of watershed-scale research have been recognized since early in the century. Research watersheds were established by the U.S. Forest Service near Wagon Wheel Gap, Colorado, in 1910 (Bates and Henry, 1928) and by the Soil Conservation Service in agricultural areas in 1935. The objectives of the early watershed studies were to determine the effects of various forest and agricultural management practices on water yields, flood peaks, and erosion losses. The "paired watershed" concept was often used to evaluate the effects. This technique required measurements of streamflow at two similar (and preferably adjacent) watersheds over a calibration period until a reliable statistical relationship between the streamflow characteristics of the two watersheds could be established. Then treatments were imposed on one of the watersheds and any changes in the statistical relationship were evaluated over the treatment period. Scientific reasoning then attempted to ascribe the mechanism(s) responsible for the changed relationship. Subwatersheds and small plots within these watersheds often were instrumented in an attempt to understand the pathways and dynamics of water flow.

Problems of scale and spatial variability of precipitation, soil, and vegetation became apparent very early and led to the establishment of much larger experimental watersheds by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture during the period 1955–1965. These watersheds and associated Watershed Research Centers were established in major physiographic and climatological regions of the United States and were intended both as representative watersheds and as field laboratories.

USGS watershed studies have a relatively short history in comparison to the agency's basic hydrologic data collection activities. Its first effort at systematic watershed research began in 1958 with the initiation of the Hydrologic Benchmark Network (HBN) (Cobb and Biesecker, 1971). The HBN came about at a time when the scientific community was concerned about the lack of a robust information base, or benchmark, for differentiating natural hydrologic and geochemical variations and changes from those due to human activities. Such a benchmark was considered vital to the development of effective environmental regulations, especially in those days prior to the enactment of the National Environmental Policy Act.

The HBN provided a nationwide network of small headwater basins that were unaffected by human activities and that were expected to remain so for many decades, thereby providing nearly pristine conditions for the study of natural hydrologic processes and trends (Cobb and Biesecker, 1971). From the beginning, however, the HBN suffered from insufficient funding. As a result, it has never been able to support a focused program of long-term, process-oriented watershed research. Indeed, it has not even been able to sustain a data collection effort sufficient to answer many hydrologic process-and trend-related questions. Currently, USGS is considering a redesign of the HBN—one that is capable of providing a more limited but more useful base of information related to benchmark hydrologic conditions.

A second USGS program of watershed investigations began in the early 1980s in conjunction with the National Acid Precipitation Assessment Program. A limited number of USGS Atmospheric Deposition and Analysis (ADA) sites were established, which, like HBN, tended to be in small headwater basins. The aim was to evaluate hydrologic and geochemical processes in basins where the only human effects or inputs to the basin would be those transported into the basin through the atmosphere. In particular, the ADA watersheds were oriented toward understanding the transport, fate, and long-term patterns of the two primary atmospheric deposition chemical species, sulfur and nitrogen.

The ADA watersheds have been successful intensive process research sites in terms of both scientific productivity and longevity. Most are still operating, although most have expanded their scientific focus beyond the atmospheric deposition issue. Importantly, these watersheds, with their emphasis on the intensive monitoring and analysis of water and geochemical cycling, follow the pattern established by the Forest Service at such sites as Hubbard Brook, New Hampshire and Coweeta, North Carolina, and the

Agricultural Research Service at the Little Washita, Oklahoma.

More recently, as part of the U.S. Global Change Research Program, USGS established a network of five Water, Energy, and Biogeochemical Budget (WEBB) research watersheds at Loch Vale, Colorado; Luquillo Experimental Forest, Puerto Rico; North Temperate Lakes, Wisconsin; Panola Mt., Georgia; and Sleepers River, Vermont. These sites were designed to improve (1) understanding of the processes controlling terrestrial water, energy, and biogeochemical fluxes, process interactions, and process relations to climatic variables and (2) the capability to predict terrestrial water, energy, and biogeochemical budgets over a range of spatial and temporal scales (Lins, 1994). The five watersheds represent diverse geographical and environmental settings and include sites that had a preexisting base of multidisciplinary research activities. For example, two WEBB watersheds are associated with National Science Foundation Long-Term Ecological Research sites—one is in a Forest Service Experimental Forest, and one is in a national park. Strong collaborative research relationships with scientists in other federal agencies as well as the academic community are a noteworthy characteristic of WEBB research activities.

The types of research being conducted at the WEBB watersheds include hillslope hydrology and geochemistry, water quality genesis, flow path delineation, physical and chemical weathering processes, hydrologic processes at different scales, and effects of seasonal freezing and snowpack on soil trace-gas fluxes, among others. Clearly, these activities have importance for issues other than global change, particularly water quality. The WEBB sites in the future will have to address a more diverse scientific agenda if they are to remain responsive to agency needs. Research watersheds are becoming too expensive for any one program or issue to sustain for more than a decade. Accordingly, for the WEBB, ADA, or HBN watersheds to remain valuable enough to warrant continuation, the USGS must begin utilizing such sites as generic research resources and abandon their use as single-issue field sites.

As new water-related problems emerged, they were either addressed at existing experimental watersheds or new watersheds were established to obtain the required data. For example, during the 1960s, several urban watersheds were instrumented (e.g., Putnam, 1972) and several studies were begun to evaluate the effects of drastic disturbance, such as surface mining on water yields, erosion, and water quality (e.g., Musser, 1970). As the potential for environmental damage by pesticides became apparent, existing watersheds, such as those operated by the ARS in Coshocton, Ohio, were utilized to make some of the first measurements of the quantities of pesticides reaching streams. Much of this early work has been summarized by Stewart, et al. (1976).

Gas sampling array for monitoring methane flux from lake and reservoir sediments through the water and into the atmosphere. There is growing evidence that lake and reservoir sediments are a major carbon sink worldwide. Source: U.S. Geological Survey.

During the 1960s, significant advances were made in the speed and storage capacity of computers, and the trend in hydrologic research shifted from experimental watersheds to development of sophisticated mathematical models of watershed behavior. Ideally, the model developments should have stimulated new and better field measurements and this was true to some extent. However, when budgets leveled off or declined in the 1970s, many experimental watersheds were closed, and in some quarters it was thought that activities at experimental watersheds were primarily oriented to data collection and that enough watershed data had been obtained. As models were critically tested using data from experimental watersheds, the scientific community has again recognized the importance of watershed research. The National Research Council's Committee on Opportunities in the Hydrologic

Sciences concluded that "hydrologic science is currently data-limited" and that "Interest in ever-increasing scale has outrun the financial support for observation, and the balance of hydrologic science is now seriously skewed toward modeling. It is important that observation and analysis proceed hand in hand" (NRC, 1991). This fact had been recognized a decade earlier by the renowned USGS hydrologist Walter Langbein. The "ability to solve complex mathematical systems has now outpaced understanding of the physical, chemical and biological processes, *or even the appropriate data*". (Langbein, 1981, emphasis added).

Throughout the late 1980s and into the 1990s, federal agencies have been experimenting with new prototypes of watershed management processes. These processes integrate traditional water resource management objectives, such as flood damage reduction, water supply, and navigation with environmental objectives such as water quality, soil erosion reduction, ground water recharge, and biodiversity conservation. Multiple-objective processes require a much more complex analysis of watershed hydrology than the engineering designs of the past, which assumed essentially static quantities of water moving through the system (water quality was generally not addressed), simple storage reservoirs, and trapezoidal channels. The new approaches, in contrast, must account for the natural landscape heterogeneity that supports ecological communities; the chemical transformations that affect water quality; and the complex interactions between water molecules, soil, and air that facilitate ground water recharge and control soil erosion rates if they are to support environmental objectives effectively.

DIRECTIONS FOR USGS ACTIVITY IN WATERSHED SCIENCE

The work of the USGS is both regional and national in scope; consequently, the agency requires efforts that are distributed across the entire country, through a range of climatic and physiographic regions. As will be discussed further in Chapter 4, the committee believes that the USGS should use information from research watersheds and data from assessment programs to build effective modeling and data synthesis efforts to move toward an integrated set of activities to address problems of importance to the nation. Just one aspect of such an integrated program—operating research watersheds—represents a potentially massive investment. The USGS cannot single handedly create and run research watersheds across the country. Fortunately, many agencies and organizations (including the USGS) currently operate research watersheds (Table 3.1), so the USGS can draw on a wealth of data and experience from an array of investigations. Further, the USGS should develop and encourage collaborative efforts with the universities Water Resources Institutes, and the 40 cooperative units of the Biological Resources Division. Involvement of students would contribute to both the USGS project and the training of water resources professionals for the future.

Despite a fairly widespread geographic distribution of research watersheds, it does not follow that all information adequate for addressing the most critical water resource and water-related environmental problems is being provided. The USGS should assess its programs and direct future efforts to help fill gaps in the knowledge base in watershed science to ensure that policy decisions can be informed by solid scientific results. In Chapter 4 the committee presents its views of gaps in the scientific knowledge base that might be targets in strategic planning for future work by the USGS.

TABLE 3.1 Summary of Active Experimental Watersheds in the United States NOTE: Most research watersheds supported through the U.S. Forest Service (FS), U.S. Department of Agriculture (USDA), and the National Science Foundation's Long-Term Ecological Research (NSF-LTER) sites are included here. Other active research watersheds operated, for example, by university researchers are not included. All cooperators may not be listed for some watersheds.

Research Site and Agencies Involved	No. of Watersheds	Watershed size Range (ha)	Data Collection History (yr)	Types of Data[a,b]
ALASKA				
Arctic Tundra NSF	2	Up to 14,300	Up to 12	1, 2, 4, 6, 7, 9, 10
Bonanza Creek NSF	1	7,500	3	4,9
ARIZONA				
Beaver Creek USDA-FS	1	111,300	Up to	
Santa Rita USDA-ARS, Univ. of Ariz.	8	1.05–4.0	Up to 21	1, 2, 7, 9, 10
Walnut Gulch	25	0.34–14,937	Up to 42	1, 2, 6, 7, 9
CALIFORNIA				
Caspar Creek Calif. Depts. of Fish and Game and Forestry, USDA-FS, Univ. of Calif.	1	907		
Chamise Creek NBS, NPS	1	4.3	Up to 15	1, 2, 4, 5, 6, 8, 9
East Fork of the Kaweah River NBS, NPS, USGS	3	16,000	1	1, 2, 4, 8, 9, 10
Emerald Lake NPS, NOS, NASA, USGS	1	133	Up to 15	1–9
Log and Tharp's watersheds NPS, NBS, USGS, FS	2	13.1–48.9	Up to 15	1, 2, 4, 5, 6, 8, 9
San Joaquin Experimental Range Calif. State Univ., Fresno, USDA-FS	1	138	Up to 60	
COLORADO				
Loch Vale NPS, USGS	1	660	Up to 15	1–10
Niwot Ridge NSF	1	546	8	1, 2, 4, 6, 9, 10

Research Site and Agencies Involved	No. of Watersheds	Watershed size Range (ha)	Data Collection History (yr)	Types of Data[a,b]
GEORGIA				
Little River, Ga. USDA-ARS	6	1,594–33,460	Up to 28	1, 2, 4, 6, 7
Panola Mountain USGS	1	41	12	1–9
Watkinsville USDA-ARS	5	1.26–7.8	Up to 56	1, 2, 3, 6, 7, 8, 9
IDAHO				
Reynolds Creek USDA-ARS	9	0.9–23,379	Up to 33	1, 2, 3, 6, 7, 8, 9
IOWA				
Treynor USDA-ARS, Iowa State Univ.	5	6.0–60.7	Up to 32	1–9
KANSAS				
Konza Prairie NSF	5	85–10,600	Up to 12	1–9
MISSOURI				
Centralia USDA-ARS, Univ. of Mo.	3	1,230–7,238	Up to 27	1–6
MISSISSIPPI				
Goodwin Creek USDA-ARS, Univ. of Miss.	14	6.1–2.141	Up to 14	1–9
Nelson Farm USDA-ARS, Univ. of Miss.	3	1.6–2.0	Up to 7	1, 2, 3, 6, 7, 8
Holly Springs SUDA-ARS, Univ. of Miss.	2	1.3–1.8	3	1, 2, 4, 5, 6, 7, 8, 9
NEW HAMPSHIRE				
Hubbard Brook USDA-FS, NSF	1	13.2	Up to 38	1–9
NEW MEXICO				
Sevilleta NSF	2	250–350,000	Up to 36	1, 2, 4, 6, 7, 9
NORTH CAROLINA				
Coweeta USDA-FS, NSF	15	<10–760	Up to 60	1–10

Research Site and Agencies Involved	No. of Watersheds	Watershed size Range (ha)	Data Collection History (yr)	Types of Data[a,b]
OHIO				
Coshocton USDA-ARS, Ohio State Univ.	24	0.26–122.6	Up to 59	1–9
OKLAHOMA				
Little Washita USDA-ARS, Okla. State Univ.	5	0.47–52,834	Up to 33	1, 2, 4, 5, 6, 7, 8
El Reno USDA-ARS	8	1.62	20	1, 2, 4, 5, 6, 7, 8, 9
Ft. Cobb USDA-ARS	2	2.1–2.55	14	1, 2, 4, 5, 6, 7, 8, 9
Woodward USDA-ARS	4	2.7–5.56	19	1, 2, 4, 5, 6, 7, 8, 9, 10
OREGON				
H.J. Andrews USDA-FS, NSF	9	Up to 6,400	Up to 11	1, 2, 4, 6, 7, 8, 9, 10
PENNSYLVANIA				
Mahantango Creek USDA-ARS, Penn. State Univ.	3	718–41,970	Up to 67	1, 2, 3, 6
SOUTH CAROLINA				
North Inlet NSF	1	53	Up to 11	1, 2, 4, 6, 9
TEXAS				
Riesel USDA-ARS	18	0.10–125	Up to 59	1, 2, 4, 5, 6, 7, 8, 9
VERMONT				
Sleepers River USACE, USGS	4	47–11,160	Up to 35	1–8
WASHINGTON				
West Twin Creek NPS, NBS, FS, Univ. of Wash.	1	58	Up to 11	1, 2, 4, 5, 6, 8, 9
WISCONSIN				
North Temperate Lakes NSF, USGS	1	12,000	Up to 75	1–10

Research Site and Agencies Involved	No. of Watersheds	Watershed size Range (ha)	Data Collection History (yr)	Types of Data[a,b]
PUERTO RICO				
Luquillo Forest USDA-FS, NSF, USGS	4	0.33–2.64	up to 28	1–9

[a] Key to types of data: 1, meteorological; 2, surface water quality; 3, ground water levels; 4, surface water chemistry; 5, ground water chemistry; 6, soil; 7, sediment; 8, land use; 9, vegetation; 10, animal.

[b] Where there are multiple watersheds, all measurements may not be made on all watersheds.

4

Scientific Opportunities for USGS

FOCUS AREAS AND ISSUES IN WATERSHED RESEARCH

Historically, the term "watershed research," as carried out by the U.S. Geological Survey (USGS), has referred to detailed studies of physical, chemical, and biological systems and processes occurring in watersheds ranging in area from 1 or 2 hectares to a few square kilometers. Scientific studies in such watersheds have focused on basic physical processes such as sediment yield and transport, streamflow generation, and rainfall-runoff relationships. As discussed in Chapter 3, investigators also have used such watersheds as natural environmental laboratories to study processes related to atmospheric deposition, acid rain, and the transport of trace constituents through the environment as well as for biological surveys and vegetation studies. The results of such work have formed the basis for much of our current understanding of hydrologic processes.

The relatively small scales of these historic research watersheds have made detailed data collection and process studies possible but sometimes have limited the transferability of the research to larger-scale problems. For example, understanding the transport and fate of pesticides in the environment is of great interest to state and federal agencies charged with monitoring and regulating pesticide use, but these agencies are commonly responsible for regions encompassing thousands of square kilometers and containing multiple watersheds. Scientific studies of pesticide transport and fate, in contrast, usually have been either site specific or confined to small watersheds.

The committee believes the USGS will need to focus its efforts on resolving important problems, even more strongly in the future than it has in the past. Thus, future watershed research programs at the USGS must focus on scientific topics having direct relevance to current and future water policy issues. This study identified six general focus areas that provide a context for potential future watershed resarch at the USGS (Table 4.1). The topics range in scope from local to regional to national and even global and will require research at a variety of spatial scales. Some topics are purely scientific, in the context of traditional watershed studies (hydrology, hydrogeology, geochemistry, soil science, engineering, biology). Many others cross disciplinary lines and may involve such areas as economics, risk assessment, toxicology, and environmental policy.

Several aspects of the focus areas and issues identified in Table 4.1 deserve mention. First, there are obvious interrelationships among focus areas, and no single focus area can be addressed in the absence of other issues. For example, most or all water quality issues have implications for water quantity and land use. Second, the range of disciplines involved is very broad, ranging from classical hydrology and hydrogeology to more general economic and public policy considerations. Third, there is a vast array of spatial scales, from site-specific studies to global issues of climatic change and carbon cycling. Finally, all the issues are relevant to the pursuit of sustainable development. The following discussion highlights some of these issues in the context of watershed research needs.

Water Quality

Water quality can have a direct impact on human health and on the health of ecosystems. Thus, protection and improvement of the quality of ground water and surface water in the United States, particularly the protection of drinking water supplies, continue to be high priorities. Protection of surface water quality has long been a concern of most federal and state regulatory agencies and involves all components of the surface water budget. Programs in the Black Earth Creek priority watershed in Wisconsin (GAO, 1995) are good examples of attempts to maintain and improve surface water quality through coordinated efforts of local landowners; concerned citizens; and local, state, and federal regulatory agencies. Most such watershed management projects have focused on agricultural areas and have a duration of several years. The projects include an assessment phase, in which the current water quality is characterized; an implementation phase, in which specific water quality improvement steps, usually in the form of best management practices, are carried out; and a postaudit phase, in which improvements in water quality are documented. Best management practices (BMPs) are activities designed to maintain or improve overall watershed quality. Typical best management practices implemented in

TABLE 4.1 Focus Areas and Example Issues in Watershed Science

Focus Area	Issues
Water quality	- Protection of ground water and surface water quality - Material transport and fate - Process scaling - Urban storm water - Sediment transport - Ground water flow in karst areas and fractured rocks - Model development and improvement
Water availability and conservation	- Water availability - Multiobjective water management - Optimization management - Ground water recharge - Ground water/surface water relationships - Consistent ground water supplies during periods of inconsistent precipitation
Land use and land use change	- Basin-wide water management - Effects of agricultural and industrial best management practices - Effects of urbanization - Effects on sediment and trace constituents - Contaminated sites and urban brownfields - Habitat protection - Susceptibility mapping
Natural hazards	- Flood hazards (erosion, deposition, structural damage, water quality impacts) - Flood forecasting - Drought - Slope stability
Climatic variability and change	- Hydrologic responses as indicators of climatic change - Hydrologic feedback to climatic change - Global carbon cycling
Aquatic habitat alteration and restoration	- Aquatic habitats in streams - Natural flow regimes - Wetlands function and restoration - Structural versus restorative approaches

agricultural watersheds include streambank erosion controls, improved storage and disposal of animal wastes, improved agricultural tillage practices, and water control structures; local landowners and regulatory agencies share the expenses of implementing these practices.

A major problem with many such watershed management programs is that the water quality benefits resulting from the management practice changes are often difficult to predict or assess using current models and field techniques. Some parameters, such as sediment loading in small upland watersheds, respond rapidly to upstream management practices, producing measurable downstream sedimentation changes in only a few months or years and within relatively short distances. However, other parameters, such as nitrates, pesticides, and trace metals, often have much longer residence times in the hydrologic system, and downstream changes in these parameters resulting from BMP implementation may not become apparent for years or decades. Further, those changes may occur far downstream. A case in point is the Big Spring Basin in Iowa (Hallberg et al., 1983), where significant reductions in the amount of nitrogen fertilizer applied to agricultural fields have so far failed to have any statistically significant impact toward reducing nitrate concentrations in ground water in aquifers below the fields or in downstream surface waters. Investigators in other watersheds have made similar observations. To quote from a recent General Accounting Office report to Congress (GAO, 1995, p. 13), "... even given rigorous monitoring, demonstrating a link between changes in land use and diminished chemical pollution is difficult, if not impossible, especially within a short time frame." Obviously, there is a need for longer-term (10- or 20-year) surveillance and research on the effects of changing land use on watersheds. The USGS has the scientific staff, data management facilities, and long-term funding mechanisms necessary to undertake just such long-term studies. Therefore, long-term evaluation of the effects of land use changes and management practices on watersheds presents significant scientific opportunities for the USGS.

Critical issues also exist for ground water quality at watershed scales. The 1996 reauthorization of the Safe Drinking Water Act included an earlier mandate that U.S. Environmental Protection Agency (EPA) provide guidelines for the establishment of wellhead protection areas (WHPAs) around public drinking water supply wells. A WHPA is the area of the land surface that corresponds generally to the hydrogeologic capture zone from which the well collects water. Local governments can, in theory, control land use within the WHPA to eliminate or reduce contamination sources, thereby protecting the quality of water produced by the well. Unfortunately, the delineation of well capture zones can be technically difficult, particularly in complex hydrogeo logic settings, and local municipalities rarely have the financial resources to conduct detailed hydrogeologic studies around each well to be protected. Many municipalities are therefore basing WHPAs on the results of simplified semianalytic or analytic element computer codes, such as those developed by Blandford and Huyakom (1990) and Haitjema et al. (1994), which account for only limited hydrogeologic complexity. The resulting capture zone estimates are therefore uncertain. Furthermore, the actual capture zone can be almost impossible to verify in the field. Clearly, more work is needed, both on field methods for assessing hydrogeologic conditions near water supply wells and on computer techniques for developing capture zone estimates.

While techniques for measuring and estimating contaminant loads and runoff from small watersheds are plentiful, tracking the fate of nutrients, heavy metals, sediments, and other contaminants in water bodies subject to large variability remains an elusive task. The physical processes affecting these substances—deposition, resuspension, and various transport mechanisms—often take place in aquatic environments where streamflow, temperature, velocity, wind, and other forces acting on those environments are subject to large fluctuations over short periods of time. Typically, it is unclear whether the fate of material in a system is being controlled by reaction or transport processes. In general, then, an integrated understanding of the biogeochemistry of sediments and subsurface environments is lacking. Without this knowledge the responses of a system to changes in inputs cannot be predicted.

The atrazine story demonstrates these challenges. Farmers have used the herbicide atrazine effectively for over 30 years in many parts of the Midwest to control invasive grassy weeds in corn and other crops. Unfortunately, atrazine has become a ground water contaminant and was shown recently to be present at trace (part per billion) quantities in over 50 percent of the drinking water wells in some parts of Wisconsin (LeMasters and Doyle, 1989). Detection of the pesticide at such low levels was not possible just a few years earlier because sufficiently sensitive analytical techniques were not yet available. The fate of this pesticide in ground water and surface water is a complex process), involving advective-dispersive transport, sorption-desorption to soil particles and degradation, as the parent atrazine compound is transformed into atleast three known metabolic products. Even though atrazine use in many parts of the Midwest currently is being banned or sharply reduced, it is likely that atrazine and its metabolites could persist at low concentrations in watersheds for many years. As a result, contaminant levels in ground water and surface water might increase as atrazine leaches downward from the soil zone. Presently there are no

BOX 4.1 ILWAS—THE SMALL WATERSHED APPROACH

The Integrated Lake-Watershed Acidification Study (ILWAS) illustrates the value of simplifying an environmental problem using the small watershed approach. ILWAS, conducted in the early 1980s by a consortium of academic, federal, and private researchers, asked a well-posed question: "In lake-watershed systems receiving similar amounts of acidic deposition, why are some lakes acidified and others neutral?" By studying small watersheds, this problem became tractable; the processes controlling water acidification and neutralization could be isolated and identified.

ILWAS was conducted in the Adirondack Mountains of northern New York, an area that receives high levels of acidic deposition and is sensitive to acidification because of its crystalline bedrock. The study focused on two small (~2 square kilometers) lake-watershed systems 30 kilometers apart. Both watersheds were pristine, forested, and had similar compositions of bedrock and glacial till. Both watersheds also received nearly identical acidic deposition (mean annual pH of 4.2). Yet Panther Lake was neutral (typical pH near 7.0), whereas Woods Lake was acidic (pH 4.5 to 5.0). Woods Lake was too acidic to support fish.

Many components of the two lake-watershed systems, including vegetation, soils, surficial geology, till and bedrock mineralogy, and in-lake features, were evaluated for four years. The chemical composition of water was monitored along its flowpath in each watershed from when it entered as precipitation until it left as lake outflow. Samples were collected of incident rain and snow, throughfall (canopy drip), soil water percolate from the organic and mineral horizons, ground water in the glacial till, inlet stream water, and lake water outflow. Changes in chemistry along a flowpath were related to the physical environment through which the water was moving (canopy, soil, till, etc.), providing the clues needed to understand the acid neutralization process.

The key to the contrasting chemical response of the two systems is differences in the catchment hydrology. Peak flow at Panther Lake outlet is more attenuated, and base flow is more sustained, relative to Woods Lake. These differences, in turn, stem from differences in surficial geology, as revealed by geophysical surveys. At Woods Lake, the till cover is relatively thin, and water infiltrates only a short distance before moving laterally downslope. At Panther Lake, till is much thicker and water follows longer flowpaths. Despite similar mineralogical compositions of the surficial material and bedrock in the two watersheds, the longer water residence time within the much deeper tills of the Panther Lake system is sufficient to allow weathering reactions to buffer atmospheric acidity.

A lasting contribution of ILWAS is the recognition that hydrology, as controlled by surficial geology, is often an important factor in determining the sensitivity of a lake or watershed to acid deposition.

verified integrated process models to predict the long-term transport, transformation, and fate of atrazine and related pesticides in ground water/surface water systems.

The tracking of contaminants from one scale to another presents many research challenges. Problems associated with extrapolating laboratory results and models to small watersheds and small watershed results to large watersheds are well documented (NRC, 1991). Models that are appropriate at one scale are not necessarily useful or practical at larger or smaller scales. Inaccurate estimates of kinetic parameters relative to transport rates particularly handicap modeling efforts. Overall, very, few models have been formulated, calibrated, and verified at larger scales. Much fundamental process-oriented watershed research is tractable only at the scale of a small experimental watershed, yet actual environmental problems usually occur at larger scales. Investigative and analytical techniques to transfer knowledge gained at small scales to watershed management and problem solving at larger scales, both spatial and temporal, are clearly lacking.

Many scientific opportunities exist for water quality monitoring and research in urban and suburban watersheds. Urban settings can deliver a broad mix of potential contaminants to surface water and ground water, and hydraulic residence times are commonly short, offering little opportunity for degradation or sorption of contaminants prior to downstream discharge. Two principal sources of rainfall-related water quality problems in urban and suburban watersheds are point sources, including both combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs), and storm-water discharges (SWDs), including nonpoint sources of pollution. Both CSOs and SSOs violate water quality standards, while SWDs also contribute suspended solids, create bed loads, and exacerbate problems associated with accumula tion and transport of contaminated sediments. In either case, transient events can create serious adverse impacts on receiving waters that have tended to defy resolution. Very little is known about the ecotoxicological impact of these periodic urban discharges to downstream regions. Best management practices for urban watersheds are still evolving. Predictions of urban storm water quality based on models developed in rural or undeveloped areas are prone to failure.

Because of its established record of achievement in data collection and assessing major point and nonpoint sources of nutrient flux in U.S. watersheds, the USGS is well suited to broaden its current activities to include complementary scientific evaluations of large urban and suburban watersheds affected by hydrometeorological events. Such an expanded focus would help identify and record the indicator parameters descriptive of the spatial and temporal impacts of discharges from the urban/suburban complex into contiguous water resources and contribute to development of policy and management strategies protective of human health and the environment.

Sedimentation studies represent additional research opportunities. There is a long history of study of sediment erosion, transport, and deposition by the U.S. Department of Agriculture's (USDA) Agricultural Research Service and Natural Resources Conservation Service and by universities, but major scientific, issues related to sedimentation remain. Perhaps the most pressing of these is in the area of contaminant transport, fate, and impact, as sediments play an important and poorly understood role in the behavior of chemicals in both surface water and ground water (NRC, 1991). Because most hydrophobic pollutants are associated with particulate material, many have accumulated to high levels in sediments and evolved into "in place" pollutants (i.e., polychlorinated biphenyl (PCBs); see, for example, Harris et al., 1988; Larsson et al., 1992). Contaminated sediments may pose a continuous threat to a system due to resuspension events or remobilization caused by biological activity (e.g., bioaccumulation, biomagnification; Harris et al., 1990; Smith et al., 1988). Once again, major difficulties encountered in scaling up research findings at individual sites to large heterogeneous watersheds persist.

Karst features and fractured rocks occur over large areas of the United States, yet methods for measuring and modeling ground water flow and ground water surface water interactions in such terrains are currently poor. Most hydrogeologic models are based on the physics of porous media flow, yet severe ground water and surface water problems occur in areas where ground water moves through underground cavities and solution channels (karst) or through interconnected fractures. Some fracture-flow models make the simplifying assumption that the fracture distribution is essentially twodimensional (Rouleau, 1988; Smith et al., 1989). Recently, several fracture-network models capable of characterizing three-dimensional fracture geometries have been developed (Dershowitz et al., 1994). These models require statistical characterization of the geometric and hydraulic properties of field-measured fracture sets. The models then simulate flow and transport through stochastically generated fracture networks. Few sets of field data exist with which to test and validate such models. Furthermore, integration of fractured rock investigations with larger-scale watershed studies has been attempted only rarely.

The variety of hydrologic processes operating in watershed systems can best be studied using integrated models, such as the Modular Modeling System described by Leavesley et al. (1996). Such modeling systems link specific process models, such as precipitation models or rainfall runoff models, to environmental data sets through a geographic information system. Such models are powerful tools that can be used to study many watershed processes in a unified fashion and are particularly useful in identifying data gaps.

Water Availability and Conservation

Water supply and conservation continue to be critical issues over broad areas of the United States. As the nation's population continues to grow, demands for additional water for potable and industrial uses will also increase, and there will be increasing pressure to find and develop new sources of ground water and surface water while maintaining water quality and quantity. On a global basis, it is estimated that society's ability to appropriate runoff will increase by 10 percent in the next 30 years, while the population will increase by 45 percent in the same time period (Postel et al., 1996). With anticipated diversions from streams, together with the potential adverse effects of global change, aquatic species may become endangered by reduced instream flows over the coming decades. Thus, there is a continuing need for reliable, up-to-date water resource information to help water managers and regulatory officials make the best possible decisions about water supply alternatives. Such decisions are impossible without considering all the competing uses and costs involved in water supply. For example, even in humid areas of the United States, increasing ground water withdrawals in a particular area may have unwanted side effects, such as diminished base flow to streams and wetlands or land subsidence. Planning decisions cannot be made without a clear understanding of the physical interrelationships between ground water and surface water systems.

Meeting current and future demands for water supply while simultaneously minimizing the financial and environmental costs of water use and treatment is an example of multiobjective water management. Recently developed mathematical models and computer codes can link various water management options to the policy constraints of each option. For example, ground water policy evaluation and allocation models can be used to study the influence of regional institutional polices, such as taxes and quotas, on regional ground water use (Wagner and Gorelick, 1987). Hydraulic management models can help determine optimal locations of pumping wells and optimal pumping rates based on a variety of restrictions on local drawdown, hydraulic gradients, water quality, and production targets. Such optimization models can be powerful management tools, but the physical hydrologic and hydrogeologic data necessary for their use often are lacking.

Future watershed management will require a better understanding of natural ground water recharge processes and of artificial recharge techniques (NRC, 1994a). Natural ground water recharge is the process by which water moves downward from the land surface to reach the saturated zone and becomes ground water. Natural recharge varies temporally and spatially and is notoriously difficult to measure (Mercer et al., 1982), yet accurate estimates of recharge rates and delineations of recharge areas are essential for most commonly used ground water models, such as MODFLOW. Field and modeling studies of recharge frequently involve several disciplines, including climatology, surface water hydrology, soil physics, geochemistry, and vaclose zone hydrology. Although several investigators (e.g., Stephens and Knowlton, 1986; Stoertz and Bradbury, 1989) have conducted detailed studies of recharge at specific sites, there have been few, if any, rigorous studies of the rates and spatial variations of ground water recharge at watershed scales.

Artificial recharge projects have become common in areas of the United States experiencing ground water shortages and usually involve the construction of permanent or temporary surface impoundments with permeable beds (NRC, 1994a). Surface water held in such impoundments is allowed to seep slowly downward to recharge underlying aquifers. More research is needed to evaluate the long-term effectiveness of such projects in sustaining local and regional ground water withdrawals and their short-- and long-term effects on water quality, both locally and throughout watersheds. It is also important to evaluate water quality issues associated with artificial recharge practices. For instance, in parts of the arid southwest, low-quality surface waters are sometimes used to recharge ground water. The risks to future users of the ground water are largely unknown.

Exchanges between ground water and surface water are key components of every watershed system, yet many past studies have focused on only the surface water or ground water aspects of particular watersheds. Over the past 20 years USGS scientists and others have conducted significant studies of the interactions between lakes and ground water systems. The early work of Winter (1978) established a framework for describing the dynamics of ground water flow into and out of lakes and demonstrated how modern computer techniques can be used to guide the collection of appropriate field data through numerical simulation of lake systems. More recent studies (e.g., Krabbenhoft, 1992; Krabbenhoft et al., 1990) have added chemical and isotopic components to understanding of ground water/lake interactions, and such studies have implications for managing lakes to avoid or mitigate such problems as lake acidification due to acid rain, eutrophication due to nutrient-rich runoff, and accumulation of toxic substances such as mercury in lake sediments and biota.

While contamination of ground water from landfills, hazardous waste sites, and underground storage tanks has come under special scrutiny during the past 15 years, much less attention has been given to the transport and fate of agricultural chemicals and nutrients in animal waste after they are applied to land surfaces. Important fractions of materials so applied infiltrate to ground water and move through shallow aquifers to nearby streams. Leakage from subsurface disposal systems also can follow similar pathways to streams. Knowledge of the fate of substances as they move through subsurface environments to surface waters is important not only in understanding the nature of contamination but also in designing management programs.

Interactions between surface and ground waters are particularly important to understanding depletion and replenishment of aquifers during drought events. The science of these processes is poorly developed, and existing capabilities to predict aquifer responses to droughts and recharging surface water events are limited.

Land Use and Land Use Change

Watersheds at various scales respond as an integrated whole to the hydrologic changes imposed on them. Most local, national, and global environmental issues involve some aspect of land use or land use change. Such land use issues range from local agricultural practice to regional timber-harvesting methods to large-scale deforestation, and most of these issues can become emotionally and politically charged during public debate. In the interest of providing clear scientific guidance to decisionmakers, it is critical that we define the scientific questions involved in each issue and then collect appropriate data to answer the questions. Watershed research provides one obvious framework in which to collect such data.

The Loch Vale watershed in Rocky Mountain National Park, Colorado. The Loch is just visible in the upper center of the photograph, beyond Andrews Tarn and Glacier, which appear in the foreground. Source: U.S. Geological Survey.

Basin-wide water management requires information about current land use. Land use/land cover inventories constructed from satellite imagery are becoming commonplace for the analysis of large watersheds. Use of this information represents a substantial advancement in watershed analysis, but its utility also can be limited by level of resolution, errors in classification, and limited precision within categories. For instance, a preferred management practice in many watersheds is the use of riparian buffers, often requiring widths of less than 10 meters to be effective. Assessment of the extent of such practices at that scale within a watershed is pushing the limits of resolution of satellite data. Information at that scale is also insufficient for identification of wildlife habitat and other ecological analysis. Higher resolution may be necessary for ecological analysis, but use of those data is currently very labor intensive. There is a need to expand coverage of computerized information at small scales.

Knowledge of land uses alone is not sufficient to adequately describe watershed processes. How lands are managed can dramatically affect these processes. For example, while cropland area in the United States changed only modestly during the past several decades, the use of fertilizer on those lands changed dramatically. From 1960 to 1980, nitrogen applied to crops in commercial fertilizers more than tripled (see Figure 4.1). It has remained essentially constant since 1980. From 1964 to 1982, agricultural uses of herbicides in the United States increased by over 700 percent (see Figure 4.2). Herbicide usage has declined slightly since 1982. Animal operations also can have dramatic impacts on nutrient fluxes in watersheds. Significant proportions of median annual loadings of phosphorus and nitrogen to agricultural and forest lands are derived from animal manure (Puckett, 1995). In some locations, loadings of phosphorus and nitrogen from animal manure can exceed the rates at which those materials can be taken up by crops (Barker and Zublena, 1995). Loadings of nutrients from this source vary by over an order of magnitude from one manure management practice to another.

The effect of urbanization on the hydrologic environment is a critical land use issue in many parts of the United States. In most population centers in the country there is an ongoing trend of suburban growth in which rural and agricultural land at the perimeter of urban centers is subdivided for housing developments and light industry. In 1982 developed areas in the United States, excluding Alaska, accounted for 4.8 percent of lands owned by entities other than the federal government. Data reported by the Bureau of the Census indicate that within a decade, from 1982 to 1992, that amount increased by 25 percent. These shifts are of much greater significance in several states. As indicated in Figure 4.3, eight states experienced more than a 40 percent increase in developed land from 1982 to 1992, and another 10 had increases in the range of 30 to 40 percent.

In many areas of land use change, wetlands have been drained or their watersheds have been significantly altered. The result of wetlands drainage often is a complete change in almost all hydrologic properties of the landscape, including such parameters as drainage patterns, slope, vegetation, surface roughness, impermeable area, and soil compaction. The watershed response to such alterations can include increased flood peaks and flood frequency, increased bank erosion, degradation of surface water quality, and reduced ground water recharge. In addition, many new subdivisions rely on individual private septic systems for waste treatment and disposal, and there

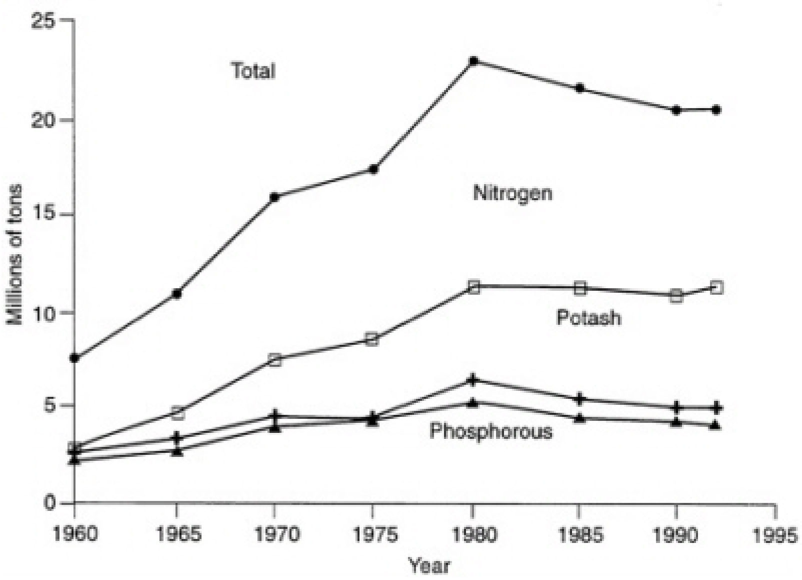

FIGURE 4.1 Commercial fertilizer applied to cropland in the United States, 1960–1992. Source: Lin et al. (1995).

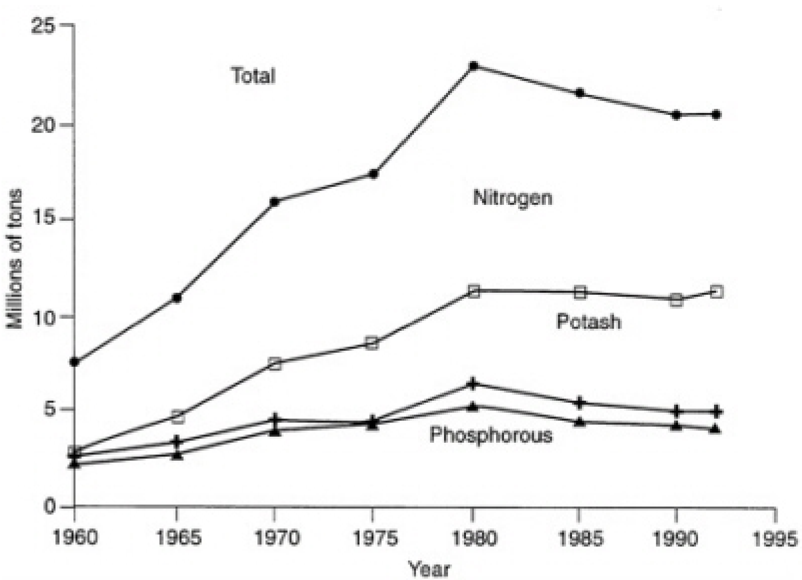

FIGURE 4.2 Pesticides applied to cropland in the United States, 1964–1992. Source: Lin et al. (1995).

is evidence that individual conventional septic systems contribute to ground water contamination (Robertson et al., 1991). What is the long-term effect of suburban development on the quantity and quality of ground water and surface water? Watershed studies in urbanizing areas are needed to help address these and related questions.

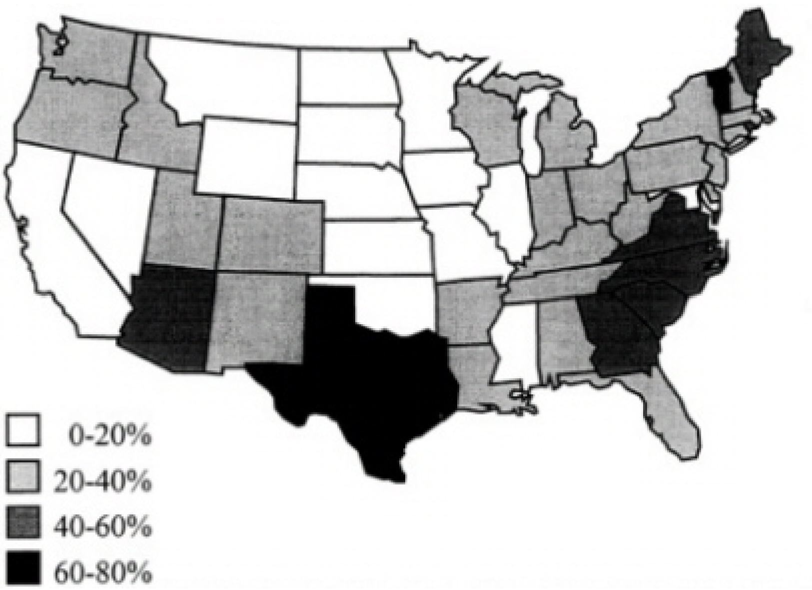

FIGURE 4.3 Percentage increase in developed land, 1982–1992.
Source: Bureau of the Census, *Statistical Abstracts of the United States*, 1990 and 1995 editions.

The fate of "brownfields," or contaminated industrial and commercial sites, is of particular concern in urban settings. These sites exist in nearly every urban center in the United States and contain some level of contamination in soil, ground water, or both. Returning these sites to "uncontaminated" status usually is not feasible technically or financially; yet if nothing is done, such sites can become abandoned urban wastelands. To resolve this dilemma, regulatory agencies have proposed relaxing some environmental standards in brownfields areas to make the cleanup process feasible and to encourage sale and redevelopment of the sites. What are the long-term implications of such policies for urban watersheds?

To help guide land use decisions, planners often turn to contamination susceptibility models to predict which parts of a landscape are most vulnerable to ground water or surface water contamination. The best known of such models for ground water is probably DRASTIC (Aller et al., 1987), which rates relative landscape vulnerability according to a few basic attributes such as depth to groundwater and soil type. Other similar models have been constructed with mixed results (NRC, 1993). A recurrent problem with all such models is assessing their accuracy. Because these models are designed to predict the probability of a future event (ground water contamination) that may or may not occur, there is little or no possibility of calibrating or verifying the models in most areas, yet such vulnerability assessments are attractive as a planning tool. Watershed studies, in conjunction with more detailed chemical transport models that integrate hydrologic events over various areas and scales, should be useful in improving the ability to design and test susceptibility models.

Natural Hazards

Geologic hazards, broadly defined for the hydrologic sciences, include such catastrophic events as floods, droughts, slope failures, and sinkhole development. Floods are the most frequently occurring natural hazard, and improved flood forecasting and real-time modeling in support of flood mitigation efforts are clearly important objectives of ongoing watershed studies. After the devastating 1993 floods in the upper Midwestern United States, the National Oceanic and Atmospheric Administration (NOAA, 1994) identified a need for longer-range flood-stage forecasts, better soil moisture information, and better precipitation models. Were the 1993 floods the result of a series of random low-probability hydrologic events? Or do the floods signal a significant change in hydrologic response related either to climatic change or long-term anthropogenic changes in watersheds throughout the upper Midwest? Watershed studies at various scales can help address these questions.

Significant progress has occurred in recent years in the capability for real-time flood forecasting. The National Weather Service is in the midst of modernizing its system for forecasting floods, including flash flood occurrences on small streams and peak stage levels and their timing on major river channels. Improved models for rainfall-runoff prediction over short and intermediate time scales are a key component of this forecasting capability. Ongoing stream gauge monitoring also is needed to calibrate and verify the predictions of flood forecast models.

Beyond the impacts on lives and property, there remain many indirect consequences of floods that are often obscure or subtle, whether occasioned by accidental releases of contaminants into the environment or by malicious or opportunistic dumping. The implications of such scenarios in the usually congested arena of the urban-suburban setting are far-reaching and often overlooked in the confusion associated with flood events. The challenges of safeguarding populations from hazardous materials swept away by flooding, monitoring pollutants from both recognized (e.g., combined sewer overflows) and unidentified or nonpoint sources, and restoring the integrity and dependability of public services, constitute only a few issues on an agenda for action that involves both short-term and long-term policy and technological decisions.

The floods of 1993 also raised significant concerns related to the fate of toxic contaminants in water and sediment. For example, Goolsby et al. (1993, p 19) report that "... the heavy rainfall and severe flooding from mid-June to early August flushed extraordinarily large amounts of agricultural chemicals into the Mississippi River, many of its tributaries, and ultimately the Gulf of Mexico.... The total load of atrazine discharged to the Gulf of Mexico from April through August 1993 (539,000 kg) was about 80 percent larger than the same period in 1991 and 235 percent larger than this same period in 1992." Toxic materials were contained in some sediments deposited by the flood waters. The flooding also caused ground water contamination in areas where flood waters overtopped well casings or ground water recharge areas. There was also significant destruction of wildlife habitat in the flooded areas, some of which were inundated for weeks. Can the impacts of future floods of equal magnitude be reduced? How long will it take the environment to recover from the effects of the 1993 floods?

Drought, at the opposite end of the hydrologic spectrum, is a more nebulous occurrence than flooding. In part, this is because a drought is more poorly defined in space and time than is a flood and, therefore, is more difficult to characterize generically. Indeed, drought can be defined differently according to one's interest or purpose (e.g., meteorological drought, hydrologic drought, agricultural drought, or economic drought). The most widely used measure of drought, the Palmer Drought Severity Index, is widely viewed as inadequate for many operational purposes, especially in hydrology. Specifying when a drought biggins and ends is particularly difficult. Research on the flux of moisture over, through, and from the land, at watershed scales, may provide the basis for deriving a better "dynamic" definition and model of hydrologic drought. One particular question that watershed research may provide an answer to is to what extent, and how, does the terrestrial hydrologic system set up, reinforce, or maintain a hydrologic drought through feedback processes? The answer to this and related questions could have significant implications for adapting more efficient strategies for managing water resources during drought periods.

Sinkholes constitute another common but poorly understood natural hazard. Sinkholes are natural features that occur in terrains underlain by carbonate rocks such as limestone and dolomite. Such terrains cover about 15 percent of the United States. Catastrophic large collapses at the land surface sometimes occur during sinkhole formation, and these sinkholes have opened beneath highways, railroads, bridge structures, building foundations, and rivers or surface water impoundments. The financial and environmental costs of sinkhole development can be significant. Sinkhole development also can contribute significantly to ground water contamination, the sinkholes acting as conduits for surface waters to enter ground water systems with little or no attenuation of contaminant loads.

Many human activities can induce or accelerate sinkhole formation. The most common cause is probably declining ground water levels due to ground water withdrawals or drainage projects. Other causes include induced recharge, construction of large surface impoundments, and vibration. A better scientific understanding of the effects of sinkholes on water quantity and quality, causes of sinkhole formation, and improved means to predict their occurrence are issues that can be addressed through watershed studies in karst and related terrains.

Slope stability and slope failure concerns compose a third major area of geologic hazards related to watershed science. Slope failures often are tied to hydrologic phenomena, such as excess soil moisture, excess precipitation, poor internal drainage, or slope undermining by erosion. For example, rising water levels in the Great Lakes during the late 1970s resulted in significant shoreline erosion and slope failures (Sterrett and Edil, 1982). Such changes in water levels are the result of interacting hydrologic and climatic processes in the watershed. The Corps of Engineers estimated that in the United States there are 925,000 kilometers of stream bank with erosion problems, about 25 percent of which are classified as severe. Average annual economic losses resulting from this erosion were placed at $295 million. The heaviest losses were estimated for California, the Arkansas-White-Red River systems, and the Lower Mississippi River Basin (Federal Interagency Floodplain Management Task Force, 1992).

Climatic Variability and Change

Watershed studies related to the general focus area of climatic change encompass a variety of issues. First among these may be the evaluation of watershed responses as *indicators* of climatic change. Watersheds integrate hydrologic and geologic processes over a range of overlapping spatial and temporal scales and preserve a record of the past in many different ways. The geomorphology and channel morphometry of a watershed are physical records of past water levels, flow regimes, and flood events (e.g., Knox, 1988). The stratigraphy and composition of sediments and soils in a watershed provide evidence of past erosion and deposition. Materials contained in the sediment column, such as fossils, pollen, and archeological relics, give clues to past biological communities. Ground water systems frequently contain geochemical or isotopic signatures that, once interpreted and understood, can help in the understanding of hydrogeologic processes operating in the past. Such paleohydrologic data are extremely relevant to understanding and documentation of climatic change on local, regional, and global scales.

Several critical issues associated with understanding how climate and hydrologic systems interact are dependent upon process-level information acquired at watershed scales. Most important is the determination of how hydrologic, geochemical, and geomorphological processes respond to shorter-term variations and longer-term changes in climatic conditions. High-resolution, event-based sampling within watersheds provides the basis for improved modeling of flowpaths and streamflow generation, weathering, chemical transport, and water quality genesis processes (Lins, 1994).

Over longer time scales the hydrologic and geologic conditions recorded within watersheds represent a spatial and temporal integration of the prevailing local- to regional- to hemispheric-scale climate. Discharge records, for example, provide a basis for determining interannual to decadal trends, as well as regional and seasonal shifts, in hydroclimatic conditions (Lins et al., 1990).

A second issue is associated with the feedback effect that the terrestrial hydrologic system has on the atmosphere. Although many of the unanswered questions relate to the atmospheric pathways of evaporated moisture and to the sensitivities of atmospheric dynamics to the exchanges of heat and moisture between land and atmosphere, realistic modeling of land surface processes at the watershed scale is essential to the successful simulation of climate at regional to global scales (NRC, 1991). Spatial heterogeneities in surface hydrologic processes exert significant effects on local to regional atmospheric dynamics. For example, several investigations have indicated that soil moisture anomalies were at least secondary contributors to the persistence of the 1988 drought over North America (Trenberth and Branstator, 1992). Identifying those effects, their controls, magnitudes, and appropriate parameterizations can only be attained through ongoing and systematic observations and analysis of watershed processes.

A third significant unresolved issue associated with long-term climatic change is that the global CO_2 budget of known sources and sinks cannot be balanced over any time scale. Several lines of evidence based on interhemispheric gradients in atmospheric CO_2 concentration, intraannual atmospheric CO_2 variation, models of ocean-atmosphere CO_2 exchange, and patterns of forest growth together suggest that the northern hemisphere terrestrial biosphere may be the sink for this "missing carbon." However, current estimates of CO_2 exchange, based on carbon inventories of ecosystems and patterns of land use change, suggest that the terrestrial biosphere should be a net carbon source.

The National Research Council (1994b) stated recently that "until the current global carbon budget can be balanced, there is little hope of predicting the future changes in atmospheric CO_2 concentration and, therefore, the radiative properties of the atmosphere that will determine future climatic changes." The NRC report outlined a number of activities for deriving a more complete accounting of the global carbon budget. These included determining (1) how changes in temperature and hydrology affect methane and carbon dioxide fluxes from tundra and boreal wetlands to the atmosphere; (2) how changes in soil temperature, moisture, and nitrogen input affect methane uptake and nitrous oxide production by temperate and boreal forests, grasslands, and agriculture ecosystems; and (3) how clearing of tropical forests for crop and pasture, and subsequent management and abandonment of crop and pasture land, affect the fluxes of CO_2, CO, CH_4, N_2O, and NO between soils and the atmosphere.

The USGS's WEBB (*W*ater, *E*nergy, and *B*iogeochemical *B*udgets) watersheds are well designed for studying these high-priority carbon budget processes. The USGS should be a critical contributor to the solution of the missing carbon problem. It has already provided some important insights on the flux of carbon in an aggrading forest ecosystem at its Panola Mountain WEBB site (see Box 4.2). There, an analysis of carbon pools indicated that aggrading forests (in this case recovering from intensive cultivation from the early, a 1800s to the early 1900s) in the southeastern United States are an important regional carbon sink (Huntington, 1995). The cultivation resulted in extensive erosion that depleted soil carbon pools. Over the 70-year period that forest regeneration has been taking place at the Panola Mountain watershed, the rate of soil carbon sequestration is estimated to be between 0.34 and 0.79 mg of C per hectare per year. The USGS work is important documentation in support of the thesis that carbon sequestration in temperate forest ecosystems may be partially mitigating the effects of increased

BOX 4.2 ATMOSPHERIC ACIDIC DEPOSITION AND CARBON CYCLING IN SMALL FORESTED WATERSHED IN THE GEORGIA PIEDMONT

At the Panola Mountain Research Watershed, near Atlanta, Georgia, the USGS has been investigating biogeochemical processes related to the influences of the atmospheric deposition of sulfur, a nonpoint source pollutant, on terrestrial ecosystems and aquatic resources. The forest and soils at Panola Mountain are representative of the southeastern Piedmont Province. Watersheds comprise discrete hydrochemical environments allowing quantification of element budgets. Monitoring stream water chemistry, basic climate, soil, and biotic variables provides a means to integrate complex biogeochemical processes and evaluate trends in water quality.

Despite the high sulfate retention capacity of soils at Panola, episodic stream water alkalinity depression is sufficient to result in net negative alkalinity during many storms because of the routing of runoff through acidified surface soil horizons and dilution of more alkaline waters associated with deeper flowpaths. The model of acidification of ground water in catchments (MAGIC) predicts that chronic sulfur loading at current rates will result in substantially more pronounced alkalinity depression during storms in as little as 20 years. Modeling also suggests that future changes in rainfall amounts or seasonal distributions that result in decreases in runoff will result in greater watershed acidification than if rainfall patterns remain the same for fixed sulfur loading.

Work at Panola Mountain Research Watershed also has investigated carbon cycling processes as they may be related to issues of global climate change. The forested watershed at Panola is representative of a broad area of southeastern Piedmont forest soils. Results of study at Panola have indicated that soils have been accumulating carbon at a rate of between 0.34 and 0.79 mg of C per hectare per year during an approximately 70-year period. When applied to much larger areas of comparable recovering forests lands in the northern temperate regions, such soil carbon accumulation represents a potentially significant flux in relation to the apparent unexplained "missing carbon sink" in the global carbon cycle.

Results suggest that there is a large potential for continued carbon accumulation at Panola. However, the rate of carbon accumulation is likely to substantially decrease over the next 50 to 100 years as forest soils begin to approach predisturbance levels. The fact that this sink is likely to decline is significant because it suggests that the role of recovering forests as partial mitigation of atmospheric loading of carbon dioxide will diminish, resulting in more rapid increases in atmospheric carbon dioxide concentrations.

atmospheric loading of CO_2.

Improving forecasts of climate change and climate variation is a topic of much current interest and one that demands additional work. Knowing that climate is an inherently dynamic feature of the planet over all time and space scales does not simplify the problem of predicting what atmospheric conditions will prevail at a certain time and place in the future. Statistical models, although useful for providing a perspective on large-scale oceanic, atmospheric, and hydrologic connections, do not incorporate the necessary dynamics for ensuring physically consistent interactions among the various components of the climate system. The most promising approach to improved prediction of climatic variability and change requires improvement of the characterization of water, energy, and biogeochemical exchanges between the terrestrial surface and the atmosphere. Long-term monitoring, analysis, and modeling of watershed processes are vital to this characterization, resulting in the attainment of improved predictions.

Aquatic Habitat Alteration and Restoration

One of the most significant contributions of watershed planning in the 1990s is the prominent role given to relationships among land use, water resources, ecological systems, and sustainable development. While cases of watershed planning in the 1990s cited by the EPA tended to highlight the flux of either sediments, nutrients, pesticides, or heavy metals from land-disturbing activities, they also point out the linkage between water quality and aquatic organisms and ecosystems. In several cases water quality was shown to be linked to the health status of wildlife and farm animals; several cases address problems of degradation of terrestrial ecosystems (U.S. EPA, 1991a, 1991b, 1992).

Aquatic habitat can be defined to include a range of areas that support aquatic organisms, from the microscale level (instream or in-lake conditions), to adjacent riparian areas, to the large scale (tributary watershed areas). Aquatic habitat alteration and destruction together are perhaps the most significant ecological problem in watersheds today, often acting as the limiting factor, controlling biological integrity (Parkhurst et al., in press; Karr, 1996; Rankin, 1996; U.S. EPA, 1996; Ohio Environmental Protection Agency, 1992).

Five factors affect overall water resource integrity—energy source, water quality, habitat quality, flow regime, and biotic interactions (Rankin, 1996; Karr, 1996). Both habitat structure and flow regime can be affected by alterations of natural habitat conditions. Habitat structure includes such factors as width/depth ratios, bank stability, channel morphology, sinuosity, pools, riffles, substrate, gradient, current, siltation, instream cover, canopy, and riparian vegetation (Barbour and Stribling, 1991). Factors that define flow regime include extreme high-and low-flow conditions, variability of flows, velocity, and storm event runoff conditions.

Disturbance of the natural flow regime of rivers, resulting in changes in the timing and quantity of flows, can have a large effect on aquatic habitats. One of the major causes of such disturbance is the construction of dams on rivers. Although dams have provided benefits for mankind, this construction on most of the large rivers in this country has transformed many free-flowing rivers into series of standing-water lakes, providing obstacles to natural migratory movement and altering the natural variability of flows. The Columbia River, which is controlled by several dams, provides an example, with the natural salmon fishery reduced to a primarily stocked fishery and with the need for fish ladders and barge transport to assist the fish in reaching spawning grounds. The placement of dams to control flooding also has moderated the pulsing action of flood flows and has reduced the natural movement of sediment and nutrients throughout aquatic ecosystems. On the Colorado River, the reduction of this pulsing flow action has led to concerns about impacts on threatened and endangered fish species that rely on fresh sediment for spawning habitat and about impacts on cottonwood trees that rely on periodic formation of sand bars to support regeneration.

Urbanization and the associated increase in impervious area also have disrupted natural hydrologic patterns, by increasing peak flow volumes and reducing the time of flow concentration, which results in very short-lived, high-flow conditions associated with storm events (Schueler, 1987). At the other extreme, many of the nation's water resources, particularly in the Southwest, have been depleted due to an overappropriation of water rights for irrigation and other uses. In many states there has been a move to allocate minimum instream flows, purchasing or exchanging water rights specifically for instream use. Transbasin movement of water from rural areas to meet the demands of water users in concentrated urbanized areas also has modified natural flow regimes.

Habitat structure can be disrupted by many of the same alterations that affect flow regime, as well as a few others. For example, channelization of waters for flood control and construction of levees disrupts the natural interaction of river and stream channels with riparian zones, floodplains, and backwater areas. The loss of this natural interaction upsets the balance of sediment, nutrients, riparian vegetation, and water (NRC, 1992a). Channelization and "hard-engineering" bank stabilization projects also result in the direct destruction of riparian and instream habitat, greatly degrading the habitat structure and ability to support biological communities. Drainage of riparian and wetlands areas for agricultural land development and filling or modification for urban development also has resulted in significant losses of aquatic habitat.

The extent of problems caused by habitat alteration has not been quantified in a comprehensive way across the country, but the NRC (1992a) estimates that approximately 1.7 million hectares of lakes is degraded, primarily due to siltation, anywhere from 5 to 70 percent of the approximately 5.1 million river kilometers in this country have been channelized, and approximately 50 percent of the nation's wetlands have been lost over the last 200 years.

Most states have not yet fully recognized the importance of habitat alterations when assessing water quality improvements. A 1992 EPA assessment of the condition of the nation's waters indicated that, of 47 states that responded in 305(b) reports (i.e., summaries of the condition of state waters), 25 did not indicate any limitations by habitat conditions (U.S. EPA, 1992). However, many other states are making progress toward including habitat measurements within their regulatory programs through integration into biocriteria and narrative water quality standards (U.S. EPA, 1996). An example is the state of Washington, which has recognized that habitat can be a limiting factor and has developed methods to incorporate habitat within its Total Maximum Daily Load program, the cornerstone of the Washington state regulatory water quality program (Washington Department of Ecology, 1996).

Restoration, defined as "returning an ecosystem to a close approximation of its condition prior to disturbance" (NRC, 1992a), can help reverse the degradation caused by habitat alterations. A wide variety of techniques can be applied to restore altered habitat areas from instream or in-lake, to riparian, to upland watershed. Restoration techniques may range from administrative solutions, like preserving floodplains as regulatory floodways or allocating water for minimum instream flows, to physical improvements like removal of dams and levees or restoration of natural meandering stream morphology (U.S. EPA, 1995; NRC, 1992a). Surveillance of both structural and functional attributes, before and after restoration, is key to determining the environmental benefits of such activities.

Restoration of contaminated or damaged hydrologic regimes and associated ecosystems to more natural conditions has become an important public policy goal in many parts of the United States. For example, restoration of wetlands environments that were previously drained or filled is now seen as important for habitat protection, biodiversity, flood control, water quality maintenance, and a host of other objectives. Recently, the concept of "wetlands mitigation banking" and "mitigation credits" has been put in place in many areas of the United States. Under such policies, wetlands destruction for some economic purpose, such as highway construction, can be allowed as long as equal or greater areas of wetlands are restored or constructed elsewhere. What is the long-term effect of such policies on watersheds? Successful restoration of hydrologic and biological systems requires an understanding of the complex hydrologic and biogeochemical processes operating in the area to be restored, knowledge of the environmental criteria (plant and animal species, water levels, chemical concentrations) desired for a successful restoration, and the steps to be accomplished for the restoration to succeed. For example, a wetlands restoration carried out by simply impounding surface water might not be successful if complex ground water/surface water exchanges are ignored (e.g., Hunt et al., 1996).

POTENTIAL FOR WATERSHED RESEARCH TO ADDRESS NEEDS

The needs for research in watershed science are very diverse (see Table 4.1). Information of the kind discussed in this report has come and will continue to come from a variety of sources. The USGS is not the only source of this information, but it is a particularly important one. The USGS is of special importance because it is a nonregulatory agency that systematically collects hydrologic data on a large number of watersheds and conducts long-term research on selected watersheds. To make the best use of its resources, the USGS must focus research on areas that can provide key information on problems of significance to the nation. This study identifies four interrelated areas for research that could form the base for USGS activities over the next decade. Information needed for management of large watersheds is lacking. Much research has been conducted on small watersheds in relatively undisturbed areas, but methods for transferring knowledge about processes to infer responses of large watersheds are not available. Urbanization creates severe hydrologic changes, but relatively little work has been done to synthesize quantitative information relative to processes that affect water quantity and quality in urbanizing areas. The restoration of damaged watersheds has become a topic of considerable national interest. The scientific bases for selecting among restoration alternatives and for measuring the effects of actions are lacking. New problems involving erosion from watersheds, especially the transport and fate of sediment-bound hazardous materials, indicate that a renewed emphasis on research on sediment transport is required. In each of the four areas mentioned above—large watersheds, urban watersheds, watershed restoration, erosion, and sedimentation—the USGS could play a pivotal role in the development of a knowledge base for effective watershed management.

The ingredients of an effective watershed research program to address the interrelated areas identified in this study include (1) a measurement and monitoring program for a hierarchy of basins of various sizes; (2) several intensively studied, small *experimental* watersheds that are run expressly to support the information needs of the overall efforts in the research areas; and (3) a modeling research program to interpret the measurements made at the large scale in terms of processes understood to be important from the small watershed experiments. The USGS already has many elements that are needed for such a research program. What appears to be lacking is the organization to forge links among the elements.

A Knowledge Base for Large Watersheds

The use of small watersheds to study hydrologic and hydrochemical processes is a staple in the research arena of watershed science. Well-known examples include studies of the effects of forestry practices (e.g., Hornbeck et al., 1987; Swank et al., 1988), effects of agricultural practices, vegetation changes, and meteorological variations (e.g., Abrahams et al., 1995; Owens et al., 1983), and of the effects of "acid rain" on streams draining small watersheds (e.g., Bricker and Rice, 1989; Williams et al., 1993). There continues to be a basic research need to work with small watersheds because questions about *processes* most often are addressed best at scales where variability can either be accounted for or minimized. There are nevertheless management issues of significant consequence to society that relate to watersheds of a size beyond that of most research watersheds. Furthermore, some important processes may be observable only in large watersheds (e.g., floodplain storage of sediments for tens to thousands of years). The USGS should organize its research efforts in watershed processes to address the need to understand hydrologic effects at the scale of watersheds hundreds to thousands of square kilometers in area.

The first of the three general requirements for an effective research program in this area—an extensive measurement and monitoring network for basins of various sizes, including major rivers—is satisfied to a large extent by the National Water Quality Assessment (NAWQA) program. NAWQA is an ambitious program that seeks to evaluate the status of the nation's water quality (NRC, 1990). The program already has achieved many successes and the effort to synthesize results from around the country (the "national synthesis") is quite active (NRC, 1994c). By design, the NAWQA program has only a modest research component. The key to making the most out of the NAWQA results will be linkages to research efforts of other programs within the Water Resources Division (for example, see Box 4.3).

To incorporate the second component of the "large-watershed research program—an integration of process studies on experimental watersheds—will require cooperation and collaboration between the USGS and other agencies. For example, the USGS can rely on the Agricultural Research Service (ARS) for research on processes related to agricultural practices and on the Forest Service for research on processes related to forestry practices. The USGS has much experience in monitoring and studying natural processes within relatively undeveloped watersheds. For the most part, manipulation experiments are not possible in these watersheds. The USGS should consider where gaps in watershed experimentation exist and keep its own watershed research program active by concentrating on these areas. For example, it might be determined that *experimentation* on hydrologic effects of urbanization is lacking. In this case the USGS could shift its efforts to implementation of such a program that would be designed to interface with information coming from the NAWQA program.

The final component needed for the success of the "large-watershed' program is an active modeling effort. The USGS historically has had great success in developing models that have bridged the gap between detailed research and more regional studies. Examples include the ground water code MODFLOW and the geochemical code WATEQ. With the exception of the relatively recent work on the Modular Modeling System by George Leavesley and his colleagues, the USGS has not had similar successes in modeling for watershed science. The success of the USGS effort in watershed research demands that this aspect of the work be recognized as an ingredient of equal importance to the measurement and experimentation portions. The overall effort will entail the use of statistical analyses and mechanistic process modeling.

BOX 4.3 SLEEPERS RIVER WEBB, NAWQA, AND THE ROLE OF SMALL WATERSHED RESEARCH IN LARGE BASIN STUDIES

Sleepers River in northeastern Vermont is the only WEBB site in an NAWQA basin. The Sleepers River WEBB study uses both a nested basin and a paired basin design to investigate hydrologic and biogeochemical processes in different land uses and at different basin scales. The outlet of the largest basin, the entire 111-square kilometers drainage of Sleepers River, was chosen as an indicator site by the Connecticut River NAWQA study. It is at this scale—approximately 100 square kilometers—that WEBB and NAWQA interface.

WEBB and NAWQA have fundamentally different scientific missions. WEBB studies are process-oriented research projects, geographically restricted to one or two land uses in a single ecosystem. Sites are generally small undeveloped watersheds where processes are more effectively isolated. The goal of NAWQA is assessment of water quality status in large river basins, which encompass a broad range of land uses and often more than one ecosystem. Both programs have in common the goal of trend detection through long-term monitoring.

The operational approaches of the two programs are likewise quite different. WEBB implements a spatially and temporally intensive sampling design to infer processes by linking closely spaced observations.

Sampling in NAWQA, by contrast, is of necessity spatially and temporally sparse, limited to that deemed necessary to assess current water quality. NAWQA indicator sites each are characterized by one dominant land use and are an attempt to isolate water quality influences of that land use. Integrator sites reveal the combined influences on larger rivers.

Process understanding gained by WEBB investigations is valuable to NAWQA. The frequent sampling in WEBB studies has shown that nutrient and contaminant fluxes are quite dynamic—information that can be used to guide the frequency of NAWQA sampling. For example, this approach was applied at an indicator site in the Hudson River NAWQA, where frequent sampling showed that pesticide transport occurs primarily during significant storms shortly after application. If streams are sampled only monthly, much of the annual export can go undetected. Sampling during snowmelt at Sleepers River likewise revealed dynamic fluctuations in nitrate concentrations that were not captured by the NAWQA sampling at the same site.

WEBB sites also serve as test sites for modeling efforts. For example, the NAWQA National Synthesis Team used TOPMODEL to map the susceptibility of pesticide runoff for the contiguous 48 U.S. states. TOPMODEL was applied to predict the percentage of overland flow in total flow, and the predictions were combined with pesticide application records to assess the risk of pesticide runoff to streams. The assumptions and generalizations needed to apply TOPMODEL at a national scale were tested directly in WEBB and other small watersheds. Issues such as appropriate digital elevation model (DEM) scale, topographic index calculation algorithm, and grid size for the final map were resolved in these research watersheds where model results could be evaluated in light of existing process understanding.

Information from NAWQA studies also can point to areas where WEBB-like studies are needed. For example, within the Connecticut NAWQA, nutrient concentrations at indicator sites varied considerably. While some sites were similar to Sleepers River, other agricultural sites had much higher concentrations, and certain urban sites had the highest of all. Nutrient export from urban and intensive agricultural basins clearly dominates the loading to the main stem and the coastal zone. Process-level understanding of controls on nutrients would be of benefit to understanding current water quality and predicting its future trend. For example, isotopic analysis to identify point and nonpoint sources of nitrate would help to indicate where water quality improvement efforts should be targeted.

As mentioned above, pieces of the ingredients for a program on "large-watershed" research already exist within the USGS. There are indications that integration of these ingredients is taking place on a selected basis. A few cases about which this committee is aware include the work of Leavesley and co-workers on the Gunnison Basin in Colorado (Battaglin et al., 1993); the work of Wolock on modeling nested basins (Wolock, 1995), which is being extended within the NAWQA umbrella and the research basin efforts at Sleeper's River (see Box 4.3); the work of Bencala and coworkers to interpret in-stream tracer studies throughout the Willamette NAWQA study on the basis of processes identified to be important in a series of small-basin experiments; and the work of Helsel (1994) to "break the scale barrier." If a way can be found to organize and coordinate these efforts, the USGS may fill an important research niche in "large watersheds."

A Knowledge Base for the Restoration of Watersheds

Hydrologic alterations made to watersheds stem from stream channelization, impoundments, wetlands drainage, deforestation, and urbanization. Although many social and economic benefits have been realized from these human activities, some areas have experienced the unintentional consequences of exaggerated flood and drought, water quality degradation, reduced ground water recharge, and habitat impairment. In response, watershed restoration—a move to recreate some of the predisturbance hydrologic processes and landscape features—has been advocated as the best means to address problems of concern. One of the challenges to future water management is knowing the effectiveness and costs to restore the hydrologic regimes and ecological functions of watersheds, where such restoration is desired by society.

Central to the success of watershed restoration is an understanding of, and ability to predict, how changes on the landscape and in water management affect hydrologic processes and ecological outcomes at different watershed scales. Some efforts to monitor and then judge the results of restoration efforts for particular landscape features, such as wetlands (Mitsch and Wilson, 1996), have been made. However, at present almost all assessment efforts are geared toward particular landscape features (e.g., wetlands or riparian zones) or to remediation of some contaminant as a target site. In evaluating the USGS program on hazardous materials science and technology, this committee concluded that the USGS should take an active role in helping to evaluate the effectiveness of remediation efforts for particular ground water areas (NRC, 1996). A similar recommendation to the USGS here with regard to restoration of whole watersheds is appropriate.

The USGS has taken an active role in providing technical assessments of alternatives in some areas where whole watershed restoration efforts are under way (see Box 4.4). As this role expands, the USGS should commit to improving the science base supporting assessment protocols for watershed scale restoration. The strength of the USGS has been in areas of geoscience: in collecting data that allow assessment of the quality of water, in gaining a fundamental understanding of what natural processes are important in the flow of water and the transport of materials (including biogeochemical reactions), and in producing models that are useful in analyzing flow and transport in natural systems. The opportunity to derive ecological implica

BOX 4.4 REDWOOD RIVER WATER MANAGEMENT PROJECT

The upper Mississippi River and its backwaters, wetlands, and floodplain forests are crucial habitat for many fish and wildlife species. The river is a major flyway for migratory birds, including up to 40 percent of North America's ducks, geese, swans, and wading birds. Many of these species breed in the prairie pothole country in the great river's watershed, including the Redwood River basin, which drains roughly 180,000 hectares of southwestern Minnesota into the Minnesota River.

Flooding in the Redwood River basin has resulted in agricultural, urban, and residential damages, particularly at the town of Marshall, Minnesota. Wetlands drainage could be a major contributing factor to increased flood peaks and flood damages in the basin. Prior to agricultural drainage, roughly 43 percent of the basin was wetlands. Roughly 19 percent of these former wetlands areas are depressional and have potential value for stormwater storage. Over 82 percent of the watershed is in agricultural use, indicating extensive wetlands drainage for agriculture. Prior to drainage for agriculture, many of the wetlands in the Redwood River watershed were closed basins that stored water during rainfall events and did not contribute directly to flows in the Redwood River.

Two flood control projects that were planned for the basin have not yet been constructed because of public opposition and anticipated adverse environmental impacts. One would divert water from the Redwood River to an adjacent river basin during periods of heavy flows. The residents of the other basin do not want to accept the water. The other project is a dam that would back water up on farm land and cause fluctuating water levels in a state-owned wildlife area.

The Redwood and Minnesota rivers are also heavily polluted by suspended sediments, fertilizers, and pesticides that largely run off of agricultural land. The state of Minnesota has initiated a "Clean Water Action Partnership" to involve communities in the cleanup of the Minnesota River basin.

Wetlands restoration and the installation of soil and water conservation practices could generate substantial benefits in the Redwood basin. Wetlands and soil and water conservation practices can significantly reduce nonpoint source pollution. The Redwood watershed is also in the prairie pothole region of the upper Midwest, one of the most important waterfowl breeding areas in the United States, which makes it a high priority for wetlands restoration. Other potential benefits of a restoration approach to flood damage reduction include reduced soil erosion and increased groundwater recharge and water supply.

A county-level joint powers board, the Redwood-Cottonwood Rivers Control Area, is taking the lead in developing a water management plan for the Redwood River watershed that would use wetlands restoration and soil and water conservation practices to reduce flooding, improve water quality, increase wildlife habitat, and provide other benefits. The board is made up of local farmers. A wide range of federal, state, and local agencies, as well as private-sector representatives are assisting with this initiative. The USGS has been involved in a hydrology work group to assess watershed models for use in predicting outcomes of various management scenarios.

tions from this knowledge has been enhanced with the recent formation of the Biological Resources Division. Building on past strengths and this new opportunity, the USGS should advance the science of whole-watershed restoration in four critical areas (1) improvements in the ability to understand relationships among watershed hydrology, water quality, and habitat; (2) helping better understand conditions prior to disturbance; (3) relating the consequences of restoring damaged sites to watershed-scale outcomes; and (4) translating knowledge gained from data collection and experimental watershed studies into models that can be used to evaluate restoration actions.

Developing the appropriate knowledge base for making informed decisions about watershed restoration will require a long-term commitment to research. Changes in water quantity and quality stemming from restoration efforts may occur over periods of years to decades. That is, interacting physical, chemical, and biological processes may take long times to equilibrate following alterations. Given the background variability in climate and weather, building the knowledge base for watershed restoration will require long-term monitoring and, possibly, long-term experiments on selected systems. Once again, the development of appropriate modeling tools to interpret and to generalize results must be recognized as being of equal importance to fieldwork.

Water chemistry sampling system in the Icacos watershed, Luquillo Forest WEBB site, Puerto Rico. Source: U.S. Geological Survey.

A Knowledge Base for Urban-Suburban Hydrology

The impacts of changes in land use on hydrology and, more recently, the combined impacts of climate change and land use, have been a focus for hydrologic research. Due to the efforts of a variety of individuals and organizations (including the ARS and the Forest Service), some quality information related to agricultural and forestry effects on watershed hydrology is available. Work on urban hydrology has been somewhat more scattered, perhaps because there is no agency responsible for determining the effects of urban and suburban land use changes. Because of this fragmentation, a concerted effort by the USGS to develop more systematic information related to hydrologic changes in response to suburban and urban development should be considered.

Research needs in the area of urban hydrology are many and varied (e.g., Heaney, 1986). The USGS cannot hope to do all of the research that is needed. Rather, the consideration should be the organization of a research thrust that would utilize existing strengths of the agency. The key is to integrate the efforts of researchers in the National Research Program with those of scientists working in the districts, either on NAWQA or other projects within the cooperative program. That is, there are efforts within NAWQA to investigate urban effects on water quality (e.g., Bruce and McMahon, 1994); there are efforts to understand recharge in urban areas (e.g., Michel et al., 1994); and there are efforts to apply simulation models to estimate the effects of urbanization on floods (e.g., Dinicola, 1994). What appears to be lacking is a coordinated program to accumulate extensive data for urban watersheds with the aim of adding to fundamental scientific understanding of processes in these watersheds and of extending and improving the ability to assess quantitatively the effects of land use changes in an urbanizing area. As with the previously discussed areas that this study has identified as possibilities for USGS emphases, the integration of monitoring, observations on small research watersheds, and modeling is critical for an effective program.

A Knowledge Base for Erosion, Sediment Transport, and Sediment Deposition

The USGS historically has been heavily involved in research on sediment transport in rivers. Over the past decade or so, there has been a decreasing emphasis within the agency on such research. The recognition that toxic chemicals often are transported in association with sediments has prompted renewed interest in work to understand sediment budgets and the processes by which sediments are removed from watersheds. The sediment budgets for large watersheds have large uncertainties (Parker, 1988). In conjunction with a concerted program on the hydrology of "large" watersheds (see above), the USGS should develop an integrated effort on sediment transport. This effort should include a measurement program for a hierarchy of basins around the United States nested so as to address issues of scaling from small watersheds to large watersheds and to record sediment inventories and processes that occur only on larger watersheds. The measurement program should be supplemented with a modeling effort to interpret the measurements and provide the framework for scaling process understanding from small to large watersheds. Special consideration should be given to urban watersheds where improved knowledge of sediment budgets may be of critical importance in understanding the effects of development on water quality and channel stability. An excellent example of what can be done is the USGS work in Puerto Rico (see Box 4.5), where basic research results in

BOX 4.5 WATER, ENERGY, AND BIOGEOCHEMICAL BUDGETS IN AND ADJACENT TO THE LUQUILLO EXPERIMENTAL FOREST OF EASTERN PUERTO RICO

The Water, Energy, and Biogeochemical Budgets (WEBB) program began funding research in eastern Puerto Rico during 1990. Sites are in and adjacent to the Luquillo Experimental Forest (LEF). Core funds come from the USGS Global Change Research Program. The Caribbean District Office of Water Resources Division (WRD) manages the program, with guidance from investigators of the National Research Program of WRD.

Multiple-paired watersheds are used to compare geologically matched, natural and agriculturally developed environments. The USGS endeavors to characterize the processes that control the distribution and transport of carbon, major, important minor, and nutrient elements through soils, downslope, and out of watersheds. The core of this program is long-term, event-based chemical sampling and physical monitoring. A feature that distinguishes this WEBB site is a strong emphasis on geomorphic processes. Additional efforts include gas exchange studies and innovation of new biogeochemical approaches such as the development of equilibrium erosion theory and the design of techniques based on in situ-produced cosmogenic beryllium-10. Geographic information systems are used to extrapolate from site-specific studies to regional scales.

Since its inception, work in the LEF has involved cooperation with the Long Term Ecological Research Program, with the International Institute for Tropical Forestry of the Forest Service, and with universities, Outside the LEF, most research has involved internal coordination with cooperator-based research programs developed by the USGS district office. The cooperators are agencies of the Puerto Rico's government concerned with hazards, such as floods and landslides, or with capacity loss in the Carraizo Reservoir, the principal water supply for San Juan.

Puerto Rico is an excellent metaphor for future development in the tropics, having problems associated with deforestation and urbanization. The linkage between the research needs of cooperators and some of the basic scientific questions established a synergy. For example, researchers asked "do landslides ultimately control much of the chemistry of tropical rivers in mountainous regions?", while cooperators asked "how can we assess landslide hazards?" Researchers asked "by what mechanisms does agricultural development accelerate erosion?''; cooperators asked "why is so much sediment being delivered to the Carraizo reservoir, so much so, that a 10-year drought provokes water rationing?" By melding the basic research envisioned in the WEBB program with cooperator-funded research, scientists came up with new and sometimes surprising answers. It was shown that denudation in the forested watersheds was at a near-steady state, whereas physical denudation in the agricultural watersheds was out of equilibrium and proceeding at an order-of- magnitude greater rate. Upland erosion in the agricultural watershed, driven by landslides, is resulting in vast deposits of colluvium and alluvium, which may indicate years of vexation for water providers.

conjunction with monitoring efforts are providing the knowledge base that will be critical for informed decisions on watershed management practices (e.g., see Guzmán-Ríos, 1989; Larsen and Torres-Sánchez, 1996; Stallard, 1995).

The basic data required for analyzing sediment transported from watersheds must be collected by using bedload samplers and flow-weighted suspended sediment sampling. The measurements are costly in terms of maintaining the gauging station and in terms of personnel. The number of sediment-sampling stations, like the number of stream-gauging stations, operated by the USGS has declined in recent years. The backbone of any scientific program on watershed erosion and related sediment transport and deposition is the collection of basic data. As with stream gauging (NRC, 1992b), careful attention should be given to supporting at least a minimal set of measurement stations for sediment transport studies.

In the area of watershed management, effective utilization of research results associated with sediment transport requires that the USGS pursue coordination with agencies charged with managing water resources. Clearly, the USGS is aware of this need, as recently demonstrated in the controlled flood on the Colorado River below Glen Canyon Dam. USGS investigators had shown that the natural annual sediment scour and fill process maintained large sand bars along the river banks, kept sand bars clear of vegetation, and kept debris fans from constricting the river. Construction of the Glen Canyon Dam retarded the large annual spring floods and led to a reduction in the size of sand bars, allowed vegetation to encroach on the channel and debris fans to build up, and caused filling of backwater areas used by native fish. As a solution to these problems, the USGS proposed to the Bureau of Reclamation a controlled flood from the Glen Canyon Dam as a way of reestablishing more natural river conditions, a proposal that was implemented successfully by the bureau in the spring of 1996.

The USGS should exploit similar collaborative opportunities where practical. For example, the ARS is leading an effort to improve models for erosion prediction (Lane et al., 1988). Through minor extensions to its existing efforts in sediment transport mechanics and modeling, the potential exists for the USGS to enhance significantly the ARS program as well as other USDA programs.

5

Conclusions and Recommendations

Based on its reviews and deliberations, and as developed in the previous chapters, the Committee on U.S. Geological Survey Water Resources Research offers the following conclusions and corresponding recommendations that should contribute to improved and more effective watershed research activity by the USGS. The conclusions and recommendations are intended to help shape the agency's overall framework for activity in this area and thus do not represent an in-depth critique of all relevant activities; they are intended to be of strategic guidance.

WATERSHED RESEARCH PROGRAM INGREDIENTS

Conclusion The ingredients of an effective watershed research effort within the USGS are (1) a data collection program for a hierarchy of basins of various sizes; (2) several intensively studied, small experimental watersheds that are run to support efforts in major program areas by providing quantitative information on processes; and (3) an active modeling program to bring process understanding to the interpretation of monitoring results and to allow extrapolation of small-watershed results to larger basins. To be effective, all of the ingredients must be integrated within a coordinated overall effort.

Recommendation 1.1 The USGS should remain active in each of the areas the "ingredients" needed for an effective watershed program. The USGS should ensure that individual efforts are integrated and that proper coordination is achieved. This recommendation echoes some of those made by an internal USGS committee, which recognized that improved technical coordination and closer linkages among watershed monitoring and research programs were needed (USGS, 1992). Issues that arise in implementing a watershed research program parallel many of the issues central to the USGS National Water Quality Assessment (NAWQA) program. For the water quality assessment mission supported by the watershed research program, there is particularly large overlap with NAWQA. The USGS should directly address programmatic linkages between watershed research and NAWQA. The newly created Biological Resources Division (BRD) has the potential to enhance the ecological assessment activities of the USGS. Work of the BRD should be integrated into the watershed activities of Water Resources Division as appropriate.

Recommendation 1.2 The USGS should make it a high priority to develop research watersheds in coordination with other federal agencies, especially the U.S. Department of Agriculture, through the Agriculture Research Service (ARS) and the Forest Service (FS). In addition, strong links should be maintained and expanded to National Science Foundation Long-Term Ecological Research sites and existing ARS and FS watersheds. The USGS can add significantly to the current resources in place at ARS and FS research sites. Strong consideration should also be given to inclusion of staff from other agencies at existing USGS watersheds. In this regard the USGS should examine its incentives structure and consider creating or enhancing staff rewards for collaborative interagency efforts.

Recommendation 1.3 Research watersheds should be developed with the intention of maintaining facilities for at least 10 years. Comprehensive observations relative to the range of assessment problems undertaken by the USGS should be made. Research watersheds ideally should represent a broad range of physical, chemical, and biological processes. Strong efforts should be made to undertake work in problem-oriented research watersheds, where specific local assessment questions can be addressed. Some research watersheds should focus on ground water, and should recognize that ground water and surface water basins do not necessarily coincide, particularly in (but not limited to) areas of karst features and topography.

Recommendation 1.4 USGS scientists have developed numerous models in ground water hydrology and geochemistry that are used by research investigators and field practitioners throughout the world. In the area of watershed science, USGS modeling efforts have not been similarly at the forefront. To be able to achieve a high level of success in the areas suggested by the committee, the USGS will have to strengthen its modeling efforts. The agency will have to develop new models that will be adaptable to solving problems beyond those typically addressed in small research watersheds and will have to invest in refining the models in application in programs such as NAWQA and cooperative grants.

ADDRESSING THE ISSUES OF LARGER WATERSHEDS

Conclusion There is a need to strengthen research related to large watersheds.

Recommendation 2.1 The USGS should organize and coordinate its efforts in several programs, notably the National Research Program, NAWQA, and the District Cooperative programs. It is critical that links be forged among the individual programs so that important issues that arise regarding large watersheds can be addressed effectively. The overall goal should be to build an integrated interdisciplinary program on *large watersheds* that focuses on assessing and understanding trends in land use, geological, hydrologic, biological, and demographic changes. This strategy will put the USGS in the position argued to be important in a recent report by the American Geological Institute (1996)—"to identify where tomorrow's hot spots will be and use this information to defuse them before they heat up." The USGS also must ensure that appropriate links are made with other agencies (see Recommendation 1.2). Several agencies, including the Environmental Protection Agency, Bureau of Reclamation, Corps of Engineers, and the National Weather Service have strong interests in work on large watersheds and should be valuable partners for the USGS. Partnerships with other agencies also may be very useful (e.g., see the tabulation in the report by AGI, 1996).

Recommendation 2.2 The level of effort in the modeling aspects of watershed activities may have to be increased substantially. Testing and verifying models across a range of scales should be a primary goal of the overall effort. (See also Recommendation 1.4.)

INCREASED ATTENTION TO THE URBAN SETTING

Conclusion A key omission from the collection of research watersheds operated by the USGS and other federal agencies is representation from urban watersheds. Detailed long-term studies of the impact of urbanization on hydrology and water quality have not been carried out to the same degree as have studies on agricultural and forested watersheds.

Recommendation 3.1 The USGS should select and monitor several urban and urbanizing watersheds. (Current work in NAWQA may satisfy this recommendation in part.) Monitoring should include water quantity and quality parameters and channel morphology. The assessment of urban watersheds should include the spatial and temporal impacts of hydrometeorological events, with emphasis on riverine floods. Principal sources of rainfall-related water quality problems in urban watersheds are combined-and sanitary-sewer overflows, storm water discharges, and nonpoint sources. These events can create perplexing adverse impacts on receiving waters.

Recommendation 3.2 A strong modeling component must be part of the agency's urban hydrology work. The USGS should support the development, testing, and verification of models for urban hydrology.

RESTORATION OF AQUATIC ECOSYSTEMS

Conclusion There is a clear need for research on the evaluation of effects of restoration of aquatic ecosystems on watersheds.

Recommendation 4.1 The USGS has taken an active role in providing technical assessments of alternatives in some areas where whole-watershed restoration efforts are under way (See the Redwood River example in Box 4.3). As this role expands, the USGS should commit to improving the science base supporting assessment protocols for watershed-scale restoration. The USGS should advance the science of whole-watershed restoration in four critical areas (1) improvements in the ability to understand relationships among watershed hydrology, water quality, and habitat; (2) helping better understand conditions prior to disturbance; (3) relating the consequences of restoring damaged sites to watershed scale outcomes; and (4) translating knowledge gained from data collection and experimental watershed studies into models that can be used to evaluate restoration actions. The new capabilities brought to the agency by the BRD should be very helpful in the work on watershed restoration.

NEW ATTENTION TO SEDIMENT TRANSPORT

Conclusion Given that toxic chemicals are often transported in association with sediments and that stream-channel erosion remains an unresolved problem in watersheds affected by urban and agricultural development, there is a need for research to understand sediment budgets and the processes by which sediments are removed from watersheds.

Recommendation 5.1 The USGS should develop an integrated effort on sediment transport. This effort should include a measurement program for a hierarchy of basins around the United States, nested so as to address issues of scaling from small watersheds to large watersheds. The measurement program should be supplemented with a modeling effort to interpret the measurements and to provide the framework for scaling process understanding from small to large watersheds. Special consideration should be given to urban watersheds where improved knowledge of sediment budgets may be of critical importance in understanding the effects of development on water quality and channel stability.

INVOLVEMENT OF STUDENTS IN WATERSHED RESEARCH

Conclusion The USGS, along with many agencies concerned with maintaining the integrity of the nation's water resources, will require a cadre of professionals educated in appropriate fields.

Recommendation 6.1 The USGS should engage students in work on watershed activities. The agency should develop and encourage active collaborative efforts with the university community, the Water Resources Institutes, and the 40 cooperative units of the BRD. One specific goal should be to employ students to work on USGS projects that would contribute to both the USGS project and the thesis or dissertation work of the student.

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Biographical Sketches of Committee Members

GEORGE M. HORNBERGER obtained his Ph.D. in hydrology from Stanford University in 1970. He also holds bachelor's (1965) and master's (1967) degrees in civil engineering from Drexel University. As Ernest H. Ern Professor of Environmental Science at the University of Virginia, he is currently interested in modeling environmental systems with uncertainty, the hydrogeochemical response of small catchments, and transport of bacteria in porous media. He is a member of the National Academy of Engineering and recently was appointed to chair the National Research Council's Commission of Geosciences, Environment, and Resources.

LISA ALVAREZ-COHEN is an assistant professor in the Department of Civil Engineering at the University of California, Berkeley. She received her Ph.D. in environmental engineering and sciences from Stanford University. Dr. Alvarez-Cohen's research interests include experimental research and modeling of microbial processes in porous media, bioremediation of contaminated aquifers, innovative hazardous waste treatment technologies, and application of cometabolic biotransformation reactions.

KENNETH R. BRADBURY is a research hydrogeologist/professor with the Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, in Madison. He received his Ph.D. in hydrogeology in 1982 from the University of Wisconsin-Madison, his A.M. in geology in 1977 from Indiana University, and his B.A. in geology in 1974 from Ohio Wesleyan University. His current research interests include ground water flow in fractured media, ground water recharge processes, wellhead protection, and the hydrogeology of glacial deposits.

KIMBERLY A. GRAY is an associate professor of environmental engineering in the Department of Civil Engineering at Northwestern University. She received her Ph.D. from Johns Hopkins in 1988, an M.S. in civil engineering from the University of Miami in 1983, and a B.A. in biology in 1978 from Northwestern University. Dr. Gray teaches physicochemical processes, aquatic chemistry, environmental analytical chemistry, and drinking water treatment design. Her research entails experimental study of both engineered and natural processes. She also studies the characteristics of natural organic matter in surface waters, wetlands, and treatment systems by pyrolysis-GC-MS. Other topics of research include the use of semiconductors to photocatalyze the destruction of hazardous chemicals, application of ionizing radiation to reductively dechlorinate pollutants in soil matrices, and ecotoxicology of polychlorinated biphenyls in periphytic biolayers.

C. THOMAS HAAN is the regents professor and Sarkeys Distinguished Professor in the Department of Biosystems and Agricultural Engineering, Oklahoma State University. He received his Ph.D. in agricultural engineering from Iowa State University in 1967. Dr. Haan's research interests are hydrology, hydrologic and water quality modeling, stochastic hydrology, risk analysis, and geographic information systems. Dr. Haan is a member of the National Academy of Engineering.

CONSTANCE HUNT received her B.S. in wildlife biology from Arizona State University and her M.A. in public policy from the University of Chicago. She is a senior program officer with the World Wildlife Fund, where she directs the freshwater ecosystem conservation program, including projects to promote restoration of the upper Mississippi River basin, coordination with South Florida restoration efforts, involvement in national water resources policy, and international river conservation efforts. Previously, she conducted interagency coordinator projects, wetland evaluations and delineations, permit processing, and environmental impact analysis while on the staff of the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

DAWN S. KABACK is a hydrogeochemist who received her Ph.D. in geological sciences from the University of Colorado in 1977. Presently, she is president of the Colorado Center for Environmental Management in Denver. Previously, Dr. Kaback managed the ground water research group (Environmental Sciences Section) at the U.S. Department of Energy's Savannah River Laboratory in Aiken, South Carolina. Her work involves aquifer characterization and development of innovative technologies to improve environmental restoration of contaminated soils and ground water. Previously, she worked for Conoco in the R&D department where she had a variety of assignments related to environmental effects of mining, geochemical exploration, and clastic diagenesis as applied to petroleum exploration.

DAVID H. MOREAU is a professor in the Departments of City and Regional Planning and Environmental Sciences and Engineering at the University of North Carolina, Chapel Hill. Dr. Moreau received his B.Sc. in civil engineering in 1960 from Mississippi State University, an M.Sc. in civil engineering in 1963 from North Carolina State University, an M.Sc. in engineering in 1964 from Harvard University, and a Ph.D. in water resources in 1967 from Harvard University. Dr. Moreau has been a consultant to United Nations Development Program, Water Management Models for Water Supply; New York City, review of water demand projections; and Water for Sanitation and Health Program (Agency for International Development), financing of water supply and waste disposal.

CYNTHIA L. PAULSON is manager of watershed services for Brown and Caldwell, a consulting environmental engineering firm, in Denver, Colorado. She received a B.A. in political and environmental science from Whitman College, an M.S. in environmental engineering from Colorado State University in 1978, and a Ph.D. in environmental engineering in 1993 from the University of Colorado. Dr. Paulson's work has focused on watershed and water quality planning and assessment, including evaluations of impacts on the physical, chemical, and biological integrity of surface waters and appropriate mitigation programs.

FREDERICK G. POHLAND is professor and Edward R. Weidlein Chair of Environmental Engineering, Department of Civil and Environmental Engineering, University of Pittsburgh. He received his Ph.D. in civil engineering from Purdue University in 1961. Dr. Pohland's research interests include environmental engineering operations and processes, water and waste chemistry and microbiology, solid and hazardous waste management, and environmental impact monitoring assessment and remediation. Dr. Pohland is a member of the National Academy of Engineering.

LEONARD SHABMAN received a Ph.D. in agricultural economics in 1972 from Cornell University. He is a professor in the Department of Agricultural and Applied Economics, Virginia Polytechnic Institute and State University, and is director of the Virginia Water Resources Research Center. Dr. Shabman has conducted economic research over a wide range of topics in natural resource and environmental policy, with emphasis in six general areas: coastal resources management; planning, investment, and financing of water resource development; flood hazard management; federal and state water planning; water quality management; and fisheries management.

MITCHELL J. SMALL is a professor at Carnegie Mellon University in the Departments of Civil and Environmental Engineering and Engineering and Public Policy. He received his M.S. and Ph.D. from the University of Michigan. Dr. Small has interests in mathematical modeling of environmental quality, statistical methods and uncertainty analysis, human risk perception and decisionmaking.

DAVID A. WOOLHISER received his Ph.D civil engineering, with minors in meteorology and geophysics, from the University of Wisconsin in 1962. Dr. Woolhiser retired from the U.S. Department of Agriculture's Agricultural Research Service in 1991 after a 30-year career and is currently a faculty affiliate in civil engineering at Colorado State University and a hydrologist in Fort Collins, Colorado. He is known for his work on the hydrology and hydrometerology of arid and semiarid rangelands, simulation of hydrologic systems, numerical modeling of surface runoff, erosion and chemical transport, and probabilistic models of rainfall and runoff. He is a member of the National Academy of Engineering.