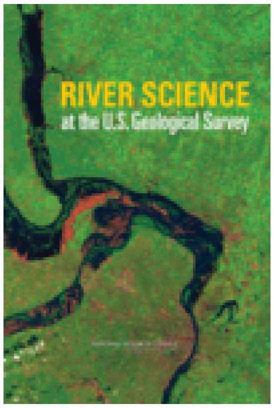

River Science at the U.S. Geological Survey

Committee on River Science at the U.S. Geological Survey, National Research Council

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RIVER SCIENCE
at the U.S. Geological Survey

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Preface

This report is one of a series of studies that the Water Science and Technology Board's (WSTB) Committee on U.S. Geological Survey (USGS) Water Resources Research has organized. Earlier studies have concerned the National Streamflow Information Program, the National Water-Use Information Program, the National Water-Quality Assessment Program, and the National Research Program, as well as areas of research such as hydrologic hazards science and watershed research.

River Science is more like the latter two studies, since there is no formal river science program at the USGS. Rather, there is a wide variety of work along rivers ranging from monitoring streamflow and water-quality parameters to integrated, watershed-based research and national synthesis. Hence, in this report where we refer to a potential future set of activities we use the less formal term "initiative" rather than "program."

As part of various strategic changes at the USGS in 2001, which included instituting matrix management to better enable integrated science, eight bureau-wide "Future Science Directions" were identified. These topical areas were coastal environments; earthquake hazards; ecosystem health, sustainability, and land surface change; energy; environmental information science; groundwater resources; invasive species; and rivers.

As part of this process, the Water Resources Discipline (WRD) was asked to create a white paper on river science, which was completed in 2004 and called "A River Science Strategy for the U.S. Geological Survey: Meeting the Needs of the Nation." The WRD sought advice from the WSTB, and in response a committee was organized to carry out tasks shown in the Summary and Chapter 1. In addition to that document, the committee considered documents in the published literature and presentations from participants at the five meetings held by the committee from June 2004 to October 2005. Committee members drafted individual contributions and deliberated as a group to achieve consensus on the content of this report.

The committee is particularly grateful for the presentations, discussions, and written submissions of the following individuals: Charlie Alpers, USGS; Steve Ashby, USACE; Larry Banks, USACE; Doug Beard, National Biological Information Infrastructure; Ken Belitz, USGS; Steve Blanchard, USGS; Nate Booth, USGS; Zach Bowen, USGS; Todd Bridges, USACE; Herb Buxton, USGS; Al Cofrancesco, USACE; Richard Coupe, USGS; Robert Crear, USACE; Bob Davidson, USACE; Dennis Demcheck, USGS; Mark Demulder, USGS; Mike Dettinger, USGS; Randall Dinehart, USGS; Paul Dresler, USGS; Earl Edris, USACE; Stephen Ellis, USACE; Andrew Fahlund, American Rivers; Craig Fischenich, USACE; Stephen Gambrell, USACE; Martha Garcia, USGS; Susan Haseltine, USGS; Bob Hirsch, USGS; Susan Holdsworth, EPA; Roger Hothem, USGS; James Houston, USACE; Brian Ickes, USGS; Rick Jenkins, USACE; Barry Johnson, USGS; Jeff Jorgeson, USACE; Wim Kimmerer, San Francisco State University; Barb Kleiss, USACE; Bill Knapp, FWS; Matt Kondolf, University of California-Berkeley; Charles Kratzer, USGS; Nick Lancaster, USGS; Matt Larsen, USGS; Mike Mac, USGS; Gail Mallard, USGS; Russ Mason, International Association of Fish and Wildlife Agencies; Johnnie Moore, Calfed; Jeff Mount, University of California-Davis; Ron Nassar, FWS; John Nestler, USACE; Mike Norris, USGS; Freddy Pinkard, USACE; Mike Reddy, USGS; Brian Richter, The Nature Conservancy; Jack Smith, USACE; Jerry Stewart, USACE; Richard Stockstill, USACE; Robert Tudor, Delaware River Basin Commission; David Vigh, USACE; Jack Waide, USGS; Steve Wilhelms, USACE; and Patrick Wright, California Bay-Delta Authority.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible and that will ensure the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: David Allen, University of Michigan; Victor Baker, University of Arizona; James Brunt, Long Term Ecological Research (LTER) Network Office; William L. Graf, University of South Carolina; Richard Hooper, Consortium of Universities for the Advancement of Hydrologic Science; Andrew Miller, University of Maryland, Baltimore; Leonard A. Shabman, Resources for the Future Inc., and Mary Stoertz, Ohio University.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommen-

dations, nor did they see the final draft of the report before its release. The review of this report was overseen by David Maidment, University of Texas-Austin. Appointed by the National Research Council, Dr. Maidment was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

We recognize that our words will not be the last words on this initiative at the USGS. Indeed, we hope that some of the ideas generated in this report will stimulate further discussions, which we hope will take place at the USGS, at other federal agencies, in academia, at nongovernmental organizations, in river basin associations, and with congressional staff, state and federal agencies, and other producers and users of streamflow data and information. We trust that these discussions will lead to new and better ways to integrate river science into the built and natural worlds.

Donald I. Siegel, *Chair*
Committee on River Science at the U.S. Geological Survey

Contents

Summary

Rivers are the circulatory system of the continents. They are the conduits for water, solute, and sediment movement from land to sea and shape much of the landscape. Throughout history, rivers have sustained communities by providing drinking water, transportation routes, waterpower, hydroelectric power, fisheries, and wildlife habitat. River bottomlands have been transformed into rich agricultural lands, and water diversions irrigate distant farmlands.

Today, rivers provide about 60 percent of the nation's drinking and irrigation water and 10 percent of the nation's electric power needs. Boating, birding, swimming, and fishing are multibillion-dollar industries. Rivers and their floodplains moderate floods and process and recycle nutrients; river sediments replenish floodplain soils and prevent the erosion of coastlines.

Human activities have profoundly changed our rivers. Deforestation, industrialization, urbanization, floodplain cultivation, dam and levee construction, and channelization have altered dramatically natural flow regimes. These changes have contributed to flooding, erosion, channel incision, contamination, non-native species introductions, and loss in ecological diversity.

The multiple and sometimes incompatible services we demand of rivers often lead to social conflicts. The policy and management decisions that surround these conflicts increasingly require the integration of science-based information that crosses traditional disciplines. Unfortunately, gaps in our understanding of river processes often limit our ability to manage rivers optimally.

THE STATEMENT OF TASK AND THE COMMITTEE'S RESPONSE TO IT

The U.S. Geological Survey (USGS) has played important roles in advancing the science of rivers and in order to help assure that its activities continue to serve the nation well, the agency sought advice from the National Research Council (NRC) as to how it might best address river science challenges by effectively using its resources and coordinating its activities with other agencies. In response, the NRC Committee on River Science at the USGS was formed to carry out the tasks shown in Box S-1. This report contains the results of that study.

The committee addresses the first task (i.e., to identify the highest priority river science questions for the USGS) in Chapter 4. This chapter proposes three topical areas, namely, environmental flows and river restoration, sediment transport and geomorphology, and groundwater surface-water interactions, for special emphasis. It also recommends two crosscutting science activities, namely, surveying and mapping the nation's river systems according to key physical and landscape features and expanding work on predictive models, especially those that simulate interactions between physical-biological processes.

Most of the second task (i.e., to identify key variables to be monitored and data-managed) is addressed in Chapter 5. Table 5-1 summarizes some key recommended variables. The chapter proposes enhancements in streamflow, biological, and sediment monitoring; these include establishing multidisciplinary, integrated reach-scale monitoring sites and developing a comprehensive national sediment monitoring program. It also encourages the USGS to be at the forefront of new technology application, including airborne lidar and embedded, networked wireless sensors.

The answers to most elements of the third task—which asks the committee to balance temporal and spatial scales, local intense studies vs. broad regional or national studies, and work on small, pristine streams vs. large, heavily impacted rivers—are topic specific. Thus, they are different for each individual recommendation. Establishment of the recommended reach-scale monitoring sites, and increased work in groundwater and surface-water interactions, imply local intense study of processes. In contrast, recommended river surveying and sediment monitoring programs would be national in scale and might last for many decades or even centuries. Overall, most of the recommended research areas, such as stream restoration, environmental flows, and models that predict ecological change, imply considerable work in highly altered rivers. However, most of these would benefit from and may require comparative sites in more pristine environments. Thus, the committee defers the details of this task to the USGS pending how it chooses to organize its scientific disciplines to most effectively address river science issues (see Chapter 6).

BOX S-1
Statement of Task

The NRC will provide guidance and advice to the USGS on the following issues:

1. Of the many river science questions, which should be a high priority for the USGS given its unique capabilities and limitations compared to other agencies (Fish and Wildlife Service, Corps of Engineers, Bureau of Reclamation, etc.), academia, and the private sector? *(Chapter 4)*
2. Which hydrologic, geomorphic, chemical, and biological variables should the USGS monitor to provide the information needed to address river science issues? *(Primarily summarized in Chapter 5, "Integrated Data Collection and River Monitoring")*

What are the new opportunities and challenges in measurement technology that should be developed and applied to River Science issues? *(Chapter 5)*

What additional benefits could be achieved through a higher degree of integration of river monitoring activities including flow, sediment, chemistry, and biota? *(Primarily Chapter 5, "Establishment of Reach-Scale Monitoring")*

Monitoring for purposes of improved understanding and regional characterization often emphasizes network designs that maximize spatial coverage with minimal temporal coverage. What scales need to be applied to spatial and temporal coverages to capture changes in principal hydrologic, ecologic, and chemical components of complex river systems? *(Chapters 4 and 5)*

In what ways do the USGS databases, spanning multiple disciplines, need to be modified to adequately store, manage, and disseminate River Science data in useful ways? *(Chapter 5, "Integrated Data Archiving, Dissemination, and Management")*

3. What should be the underlying design principles behind USGS River Science research? *(Chapters 4, 5, and summarized in Chapter 7)*

What are the appropriate temporal scales (years versus decades) and spatial scales (single site, short reach, small watershed, major basin) that should be employed in USGS river science studies?

What should be the balance between intense studies of individual systems, and broader regional or national studies?

Where should most of this work take place (e.g., small, fairly pristine streams; moderate to large rivers which are significantly affected by land uses such as agriculture and urbanization; or large, highly modified rivers)?

WHAT IS RIVER SCIENCE?

The term "river science" refers to the study of processes affecting river systems. River science integrates multiple disciplines; it includes the study of how hydrological, geological, chemical, and ecological processes interact to influence the form and dynamics of riverine ecosystems and how riverine ecosystems in turn influence these processes across multiple spatial and temporal scales.

River science seeks to understand the linkages between river-related processes and patterns at multiple scales, from small streams to large rivers, from pristine to heavily urbanized watersheds, and from daily- to century-scale dynamics. Watersheds range in size from under one to thousands of square kilometers, and a river's physical and biological environment changes as water moves downstream. Small-scale or short-term physical processes may influence reach-scale habitat features that in turn influence ecological processes at broader scales and over longer time periods. River science includes the study of relationships between watersheds, riparian zones, floodplains, groundwater, headwaters, and downstream rivers. *Thus, river science is not constrained by any arbitrary spatial scale or physical boundaries defined by the morphology of channels, floodplains, or terraces. Rather, its domain and bounds are defined by the scales necessary to understand and predict river processes.*

MAJOR RIVER SCIENCE DRIVERS AND CHALLENGES

The nation faces many complex challenges in its stewardship of natural resources. In particular, human alterations of river systems have become so pervasive that society can no longer ignore their impacts. Today's policy and management challenges in ecological restoration and dam removal, relicensing of hydropower facilities, invasive species, water allocation, climatic variability, urbanization and other land-use changes, and water quality have also become significant drivers for river science.

Human and natural actions have caused the loss or degradation of riverine habitat. Throughout the country, thousands of ecological restoration efforts are being undertaken to improve water quality, manage riparian zones, improve habitat, and stabilize streambanks. Billions of dollars are being spent on small projects and billions more on major restoration projects in the Everglades, coastal Louisiana, and the upper Mississippi River. Yet the science of river restoration—how to best restore these ecosystems—is still in its infancy. Dam removal is a particularly high-profile form of river restoration, with enormous impacts on hydrologic and ecological processes. In the United States there are about 76,000 dams that exceed 2 meters in height and several million smaller ones. Recently, the removal of dams has accelerated. Their structures are becoming obsolete and therefore their economic viability to owners is declining, while at the same time legal and financial liabilities are growing and governments are increasingly recognizing the environmental benefits of their removal. To target the best candidates for removal the costs and benefits of their removal must be weighed; this requires a better understanding of how river systems respond to dam removal.

Hydropower dams are subject to periodic relicensing by the Federal Energy

Regulatory Commission (FERC). In the relicensing process, dam operators must discuss the impact of their operations on the riverine environment and how they might mitigate any negative impacts. Citizen groups and environmental nongovernmental organizations use this as an opportunity to advocate for dam removal or operations modification. Many of their concerns center on the timing and volume of water releases and their impacts on water quality and instream habitat. Addressing these concerns rests on our ability to predict such impacts.

Human actions have spread thousands of invasive species across the nation, including saltcedar in watercourses throughout the western United States, Asian carp in the Mississippi and Illinois Rivers, and zebra mussel in the Great Lakes and elsewhere. Insufficient knowledge exists about how these species spread, how to limit their spread, and how they influence river biodiversity and ecosystem processes.

Severe drought in the western United States and the potential need to reallocate waters of the Colorado River to cope with its prolonged nature, has heightened awareness of water allocation issues. These large-scale issues, coupled with numerous conflicts over smaller streams, involve battles between interests concerned with municipal and agricultural water supply, environmental flows (i.e., flow levels, timing, and variability), and recreation. River science can provide information for decisionmakers working to resolve such allocation conflicts.

The ecological and sociological impacts of climatic variability have been and will continue to be significant. Reduction in precipitation or change in the timing of snowmelt can severely impact agricultural production and increase conflicts among water users. Variations in temperature and the duration, magnitude, and timing of high and low flows affect the quality of river habitat. These impacts are just beginning to be understood.

The quantity and quality of river flows are tied directly to changes in urban occupancy and rural land-use activities. Even seemingly minor changes in land use can create significant changes in runoff patterns. Our ability to predict future water availability and flood risk, manage erosion and siltation, and manage river ecosystems is thus limited by our understanding of these land-use changes.

Despite recent improvements, our nation's water quality remains at risk. As of 2000, only 61 percent of assessed stream miles fully supported all of their designated uses, and of these, 8 percent were considered threatened for one or more uses. In the remaining assessed reaches, one or more designated uses are impaired by pollution or habitat degradation. High-priority water-quality problems include bacteria, nutrients, metals, siltation, and emerging contaminants such as pharmaceuticals.

The scientific understanding necessary to respond to these challenges will not come easily. The approach must be multidisciplinary and integrative, and it must be process-based and predictive. River science can provide such an approach.

Recommendation: USGS river science activities should be driven by the compelling national need for an integrative multidisciplinary science, structured and conducted to develop a process-based predictive understanding of the functions of the nation's river systems and their responses to natural variability and the growing, pervasive, and cumulative effects of human activities.

THE ROLE OF THE USGS

The demands for river science information cannot be met by any one organization. Given the number of entities studying rivers—including federal, state, and local agencies, public and private institutions, universities, and the public—what is the role of the USGS in river science?

The USGS has collected river-related data since the 1800s, emphasizing consistent methodology and quality control. It is the primary science agency of the Department of the Interior, with strengths in hydrology and hydraulics, sediment transport, biology and ecology, aquatic chemistry, hydroclimatology, geology, and resource mapping. The USGS also has a reputation for impartiality because of its lack of regulatory authority; and it has abundant interconnections with academia, federal natural resource agencies, and local and state agencies. For these reasons, the USGS is ideally suited to provide "policy relevant and policy neutral" information and understanding to develop the integrative multidisciplinary river science initiative envisioned in this report, including bottom-up (driven by individuals or small teams), top-down (organized through an institute initiative), and community-driven (originated to support a particular management concern) science. In addition, the USGS is uniquely positioned among federal agencies to provide integration and synthesis to many ongoing river science activities.

Recommendation: The USGS should establish a river science initiative to bring together disparate elements of the USGS to focus its efforts to deal with growing river science challenges. The initiative should build upon USGS's history, mandate, and capabilities. It should take advantage of key attributes of the institution, such as its

1. **mission as provider of unbiased science information,**
2. **multidisciplinary staff,**
3. **data collection and monitoring expertise,**
4. **experience in science synthesis at many scales, and**
5. **organizational structure that combines national research programs with state-, watershed-, and university-based cooperative programs.**

In carrying out the initiative, USGS should closely coordinate with other federal agencies involved in river science and related activities.

SCIENCE PRIORITY AREAS FOR USGS RIVER SCIENCE

Society has a clear need for river science, and the USGS has a variety of strengths and capacities that can be brought to bear on these needs. The intersection of society's needs and the USGS's strengths suggest a number of science priorities for USGS river science. These priorities are grouped into crosscutting science activities and topical science focus areas where recommendations for USGS research are offered.

Crosscutting Science Activities

The following two science priority areas are disciplinarily crosscutting activities that would strengthen the holistic river science approach. These activities would underpin the USGS's science contribution to a broad national effort in river science.

Surveying and Synthesizing

River networks are intimately connected to the landscape and are integrators of climatic, geologic, and land-use processes within their watersheds. Throughout the nation, there are large regional gradients in climate, geology, topography, land cover, and human impacts. This extensive variation makes meaningful generalizations about how streams and rivers function challenging and complicates how information collected in one river can be transferred to another, geographically distant river. Therefore, generating a national baseline survey that characterizes the spatial variation in key landscape features and processes would provide insights into the controls of in-stream river processes and allow for more cross-site comparisons.

A multidisciplinary survey and mapping of rivers and streams should provide a preliminary structure of multiple information layers at a reach scale. This stratification of information would be based upon readily available data, including climate, topography, soils, and geology. It should also include land use and human alteration information, such as upstream diversions and impoundments that alter the flow regime. Many other elements necessary for this collection of data layers are now available in the National Hydrography dataset products that are under development in partnership with the U.S. Environmental Protection Agency. Ultimately, this mapping effort would provide an important resource nationally useful to risk-based analyses of floods, invasive species spread, and many other issues.

Recommendation: The USGS should survey and map the nation's stream and river systems according to the key physical and landscape features that act as determinants of hydrologic, geomorphic, and ecological processes in streams and rivers. This synthesis will provide a scientific baseline that can be used to support many regional-scale river science questions and afford geographic information of use to state and federal agencies, academia, and the public.

Modeling River Processes

Quantitative models that integrate physical, chemical, and biological processes provide detailed information on pathways and interactions that are difficult to measure directly in the field or whose characteristics change over time. Models complement point measurements and surveys by interpolating across the data and providing a mechanism to predict future changes. The USGS has a 40-year history of developing mathematical models of natural systems, including estuarine ocean circulation, surface-water runoff and river hydraulics, groundwater flow and solute transport, sediment transport, biological processes in streams, and groundwater and surface-water interaction. The USGS is unique among federal agencies for its breadth of modeling applications.

Potential applications of predictive integrated models are many. The construction of ecohydrologic models that focus on the structure of stream flows coupled to models linking flow to watershed and meteorological variables could be used to test the physical and ecological response of river systems to changes in flow regime with changing climate or anthropogenic drivers. These models, if properly multidisciplinary and robust, could be invaluable in river restoration, planning, and multiple water resource issues. Models can also be used to address how flow can be decreased by groundwater pumping or enriched in excess nutrients from agricultural fields.

Recommendation: The USGS should add capacity in developing predictive models, especially models that simulate interactions between physical and biological processes, including transport and transformation of chemical constituents, pollutants, and sediment. These tools provide the underpinning for predicting ecological change.

Topical Science Focus Areas

The following three priority areas are designed to address gaps in specific research areas for which improved scientific knowledge is needed. Each of these science activities will occur through enhanced monitoring and modeling, and will be key components of the overall river science framework.

Environmental Flows and River Restoration

The nation is spending billions on riverine restoration and rehabilitation projects, yet the science underlying these projects is not currently well understood and thus the approaches and their effectiveness vary widely. Therefore, a fundamental challenge is to quantitatively understand how rivers respond physically and biologically to human alterations from dredging to damming, and to specifically address: What are the required "environmental flows" (i.e., flow levels, timing, and variability) necessary to maintain a healthy river ecosystem? And which biota and ecological processes are most important and/or sensitive to changes in river systems?

For future restoration projects to be most successful, they should be adaptively managed. This requires long-term monitoring of quantitative measures of flow regime, groundwater activity, and ecosystem responses, such as primary productivity and habitat diversity along targeted reaches. Quantitative models relating ecological function to flow regimes are also needed to allow natural resource managers and citizens to forecast the impacts of proposed water management decisions. These efforts need to go beyond just stating the potential impacts of policy and management decisions to actually assessing the outcomes these activities have on rivers. Improving and synthesizing the scientific information on environmental flows before, during, and after river restoration could lead to an improved ability to predict outcomes and thus more effective, cost-efficient habitat restoration.

Recommendation: The USGS should develop the means to characterize environmental flows in rivers by developing quantitative models that link changes in the ecological structure and function of river ecosystems (aquatic and riparian) to management-scale changes in river flow regimes.

Recommendation: The USGS should, in cooperation with and support of other federal agencies involved in restoration, serve as a leader to evaluate the scientific effectiveness of river restoration approaches to achieve its goals, synthesizing results from past restoration efforts, and designing standard protocols for the monitoring and assessment of river restoration projects.

Sediment Transport and Geomorphology

Erosion, transport, and deposition of sediments in fluvial systems control the very life cycle of rivers and are vulnerable to changes in climate and human landscape alternations. Yet, compared with water quality and quantity information, there is relatively little available information on sediment behavior in river systems, particularly large-order reaches. By advancing basic research on sediment transport detection, quantification of bedload, suspended load, and wash load, and monitoring flow velocity and water temperature associated with such sediment transport conditions, the USGS could better detect morphologically significant flows, develop methods to mitigate future problems arising from sediment movement, and play a guiding role in multiagency efforts to deal with the increasingly important national sediment challenges.

To assess sediment fluxes, sediment transport technology needs to be advanced by the USGS in partnership with other research entities. These advances could be applied to problems such as determining the risk of contaminated sediment resuspension, designing and maintaining flood control channels, predicting channel behavior, understanding sedimentation and hydraulic roughness in mountain channels, restoring and remeandering previously channelized streams, assessing the impact of dam removal on river sedimentation and habitat, estimating flows needed for removing sand and silt from gravel-bed streams, and improving sedimentation management in lakes and reservoirs. Knowing the science of these sediment-related processes is critical to the multibillion-dollar efforts to restore wetlands, reestablish flow regimes, and maintain river reaches for transport.

Recommendation: The USGS should increase its efforts to improve the understanding of sediment transport and river geomorphology in the nation's rivers. Activities should include advancing basic research on sediment transport processes, developing new technologies for measuring fluxes of bedload, suspended load, and wash load, and monitoring flow velocity and water temperature associated with such sediment transport conditions.

Groundwater and Surface-Water Interactions

River flows throughout the nation are affected when groundwater that normally discharges to rivers is captured for agriculture or other uses. Yet few of the USGS's approximately 7400 active stream gages or hundreds of monitoring wells incorporate data on groundwater and surface-water exchange. Limited investigations have been done on the end members of potential hyporheic interactions—large-scale effects of water supply developments adjacent to large rivers and detailed hyporheic interactions on first-order streams—but the full continuum of how groundwater and river water interact is relatively unknown.

The USGS has the tools, datasets, and existing networks that make it a logical place to focus resources to investigate stream-groundwater exchange processes at a national scale. The USGS has been a leader in developing many hydrologic methods and tools used to characterize groundwater and surface-water interactions. This, combined with the USGS's extensive streamgaging network and synoptic survey datasets, provides an important foundation. Lake and reservoir studies of the USGS, with some modification, provide a template for the development of an aggressive data mining effort and provide approaches to new field instrumentation of exchange rates.

Recommendation: The USGS should expand its current river monitoring and river study programs so they fully integrate the floodplain, channel, and groundwater, and the exchange of water between these systems (hyporheic exchange). The exchange of water between groundwater and rivers needs examination and quantification at multiple scales in a range of different hydrologic and geologic settings, as this process is a key component influencing river discharge and water quality, geomorphic evolution, riparian zone character and composition, and ecosystem foundation, maintenance, and restoration.

MONITORING AND DATA MANAGEMENT FOR USGS RIVER SCIENCE

A river monitoring strategy and a data management infrastructure are needed to support the proposed activities in river science. The following sections on integrated monitoring and management recommend an approach to handling the diversity of information and data that would be generated by these science activities.

Integrated Data Collection and River Monitoring

Monitoring our nation's rivers is the foundation of USGS's contribution to river science. Historically, the USGS has been a leader in river monitoring, distinguished for its scientific rigor, quality control, and innovative river monitoring techniques and instrumentation. Therefore, the USGS is well positioned to fulfill the growing need to concurrently monitor hydrologic, geomorphic, chemical, and ecologic river conditions.

Currently, streamflow data are available for many higher-order river systems, but data on water quality, sediment transport, biology, and ecology are often lacking. To make gage data more useful for river science initiatives, the USGS should investigate cost-effective ways to collect more integrative biophysical data. The USGS should consider the incorporation of index biological reaches, where coupled measurements of river flows, groundwater levels and fluxes, and water quality are combined with riparian cover mapping. The USGS should prioritize based on those variables with broad science and management applications, and seek opportunities to collaborate with other programs that monitor rivers so efforts build on and do not duplicate one another.

By building on its existing capabilities and leading an effort to enhance river monitoring to fill the science data gaps in critical or neglected areas, the USGS will be able to better support all its priority research areas in river science.

Recommendation: The USGS should expand its monitoring activities on rivers to better incorporate river physical, chemical, and biological conditions within its existing river and streamflow monitoring programs. Its goals should include development of a 21st-century river monitoring system for data collection, transmission, and dissemination.

Integrated Data Archiving, Dissemination, and Management

Integrative river science is supported by diverse measurements and observations. In contrast to streamflow data and point measurements of nutrient concentrations, observations to support river science include two-dimensional data and observations describing stream channel geometry, time-varying data on bed forms, channel sediments, and the land uses and vegetative cover of riparian corridors and upstream drainage areas. Three-dimensional data describing flow velocity fields are now available from innovative acoustic Doppler technologies that have been enhanced by USGS, and even four-dimensional measurements (i.e., time-varying, three-dimensional fields) are both technologically and economically practical data forms with great potential value for river science. The USGS maintains and stores considerable information in databases including the National Water Information System (NWIS), National Water-Quality Assessment (NAWQA) program Data Warehouse, National Biological Information Infrastructure (NBII), and The National Map.

It is in the national interest for river science data holdings to be standardized and archived in a consistent way with sufficient ancillary information (metadata) to provide traceable heritage from raw measurements to useable information and allow the data to be unambiguously interpreted and used. Coordination and cooperation among the federal resource management agencies and their nonfederal partners will be critically important as the scope, scale, and intensity of data needs to support river science evolves. No single federal agency can collect, quality assure, manage, and disseminate all data and observations relevant for river science. Yet all federal agencies, nonfederal partners, and stakeholders with an interest in river science data will benefit from access and availability of accurate, reliable, and well-documented data. A common data model would provide an intellectual framework under which river science data holdings are catalogued and accessible. To develop such a model, a strategic plan put together by informatics experts from the USGS and other agencies and academics needs to be developed.

Recommendation: The USGS should include in its river science initiative an informatics component that includes developing a common data model for river science information that can be used to archive the diverse river science metadata and data. This data model should be developed in coordination with and capable of supporting other federal agency river science data needs. The data model should accommodate data from multiple sources, including nonfederal sources. Such a program would facilitate the integration and synthesis of river science data to address the diverse range of river science questions discussed in this report.

ORGANIZING AND MANAGING RIVER SCIENCE AT THE USGS

River science at the USGS and elsewhere covers a wide variety of basic and applied research and usually incorporates a broad range of partners. Because the USGS has strengths in many of the subdisciplines of multidisciplinary river science, there may be no single best institutional "place" for a river science within the current structure of the USGS.

Future river science coordination mechanisms within the USGS should incorporate certain key strengths within existing USGS programs. These include the place-based experience and long-term datasets of some of the Biological Resources Discipline (BRD) Science Centers and Priority Ecosystems Science sites, two-way flow of information between the Water Resources Discipline (WRD) personnel doing research and those doing applied science, the close links with universities of the BRD Cooperative Research Units and many of the WRD Science Centers, and the close ties between the BRD Science Centers and other federal agencies and between the WRD Science Centers and state and local agencies. These coordination efforts should work closely with programs within the USGS's Geography Discipline and National Geospatial program office to build on the wealth of existing mapping capabilities. They should also further promote the consistent data collection standards and national synthesis strengths of the USGS.

Overall, the current fragmented nature of the USGS's approach to river science needs organization and focus. Any managerial approach that addresses river science must be born of an institutional culture that fosters integrative cooperative research. An initiative that contributes fully to regional and national needs will require interdisciplinary research teams that, if not housed together, are regularly brought together to plan, direct, and execute USGS river science activities.

Recommendation: The USGS should employ innovative managerial approaches to combine the best elements of existing Water and Biological Resources river programs and other USGS programs, and refocus a portion of existing research and field team efforts on examining and answering nationally important river science questions.

Overall, society's linkages to rivers run deep and these linkages—from agriculture to transportation and from water supply to recreation—drive a broad need for advances in river science. The USGS, by virtue of its unique strengths among the many actors in river science, has an important part to play in meeting this need. By showing leadership in monitoring, modeling, surveying, synthesizing, and data management—concerning topics such as environmental flows, behavior of sediment, and groundwater and surface-water interactions—the USGS can contribute a great deal toward answering some of the most difficult and interdisciplinary questions involving rivers. Wise application of the knowledge gained will lead to better, more informed policy and management decisions throughout the nation.

1

A Rationale for River Science

Rivers are the circulatory system of the continents (Gomi et al., 2002). They are the conduits for water, solute, and sediment movement from the land to the sea and shape much of the landscape. Rivers have distinct biological and ecological qualities, which are driven by their flows and capacity to store materials and nutrients.

Throughout history, our society has valued rivers and their riparian areas both economically and aesthetically. Indeed, rivers are part of our nation's collective consciousness; they are entwined with American history, folklore, art, traditions, and literature. Our nation's rivers have provided drinking water, fisheries, and game habitat that sustained communities built along riverbanks (Haites, 1975). Early on, they were vital transportation routes and sources of waterpower. River bottomlands have been transformed into productive agricultural lands, and water diversions irrigate vast farmlands using water that is far removed from its river source. Our rivers have also served as navigation channels, transporting goods as the nation expanded. Hydroelectric power, harnessed primarily in the 20th century by the damming and diversion of rivers, helped supply the nation's growing electrical power needs. By the end of the 1970s, dams had been constructed on most of the nation's largest rivers for hydropower, irrigation water, flood control, navigation, and other benefits.

We continue to depend on rivers today. Rivers provide about 60 percent of the nation's drinking and irrigation water (http://water.usgs.gov/pubs/circ/2004/circ1268/, revised February 2005) and 10 percent of the nation's electric power needs (http://www.ieahydro.org/Bur-Recl-web/questions/history.htm). Boating, birding, swimming, and fishing on rivers and their reservoirs are multibillion-dollar industries. Other indirect benefits that rivers and their riparian zones provide are becoming common wisdom (Malanson, 1993). For example, rivers buffer and attenuate flood peaks by storing water in their floodplains. Attendant sediment deposition replenishes floodplain soils, and within the floodplains, microbes help to efficiently process and recycle nutrients. Additionally, the sediment remaining in the river is transported downstream where it replenishes beaches and deltas.

Viewed from a scientific perspective, American society is conducting a great, uncontrolled experiment on the interconnected river systems of the nation, and human activities have profoundly changed the nature of our nation's rivers. Today, few rivers are pristine or free flowing. Beginning with deforestation by European settlers for agricultural land use in the 1700s and continuing with urbanization, floodplain cultivation, dam and levee construction, and channelization, human activities have dramatically altered natural flow regimes. These changes have often exacerbated natural flooding, such as when spring snowmelt on the Red, Mississippi, and Missouri Rivers covered large swaths of the continental interior with attendant loss of life and property damage (Barry, 1997; Shelby, 2003). Enhanced sediment erosion and transport often accompany such floods, and in the process, rivers become incised and ecological diversity is lost. Modifications to natural flow regimes have led to declines in commercial river fishing in California, New England, the Southeast, the upper Midwest, and most recently the Northwest where human activities have disrupted the life cycle of salmon (NRC, 2004a).

The introduction of non-native species has decimated native fish populations in some cases (USGS, 1998). Water quality has suffered from deforestation, tillage, and urbanization. Industrial, domestic, and agricultural wastes frequently contaminate rivers. Trace metals, arsenic, organic contaminants, excessive loads of nitrogen and phosphorus, human pathogens, and thermal discharges from power plants are present in the nation's surface waters. Overall, the degradation of rivers and their riparian ecosystems has impacted flood storage, aesthetics, fisheries, clean water, and other river-related goods and services that the nation has come to value and depend upon.

NATIONAL INTEREST IN RIVER SYSTEMS

River goods and services, and thus the conditions of rivers and riparian ecosystems, are important at local, regional, national, and international levels. Rivers cross state and international boundaries, and actions in one state have impacts elsewhere. Therefore, not surprisingly, there has been a long-standing national interest in river systems.

In the past, the national interest was focused on the human utilization of river resources. In 1851 the Supreme Court defined navigable waterways for federal responsibility as streams that served interstate or international commerce, and subsequent rulings were very liberal in defining navigation. As early as

1894, Congress appropriated funds to the USGS for "gauging the streams and determining the water supply of the United States" (U.S. Statutes at Large, v. 28, p. 398). Indeed, from early on the USGS was given the mission and thus the responsibility of managing these streams, which were defined by law as "waters of the United States" (U.S. Army Corps of Engineers Regulations, 33 CFR Part 328, Definition of Waters of the United States, http://www.usace.army.mil/inet/functions/cw/cecwo/ reg/33cfr328.htm).

In 1925, Congress directed the U.S. Army Corps of Engineers and the Federal Power Commission (a joint committee of the Departments of War, Interior, and Agriculture) to identify navigable rivers and their tributaries where hydroelectric power development would be practical. The information was to be used to formulate "general plans for the most effective improvement of such streams for the purposes of navigation and the prosecution of such navigation improvement in combination with development for power, flood control, and irrigation" (Buie, 1979). After the devastating Mississippi River floods of 1927, Congress called on the Corps of Engineers to protect the vast floodplain lands of the lower Mississippi by building levees, floodways to divert excess flows, and flood control reservoirs on its major tributaries. And in the midst of the Great Depression, the Tennessee Valley Authority was authorized in 1933 to build dams to control floods, improve navigation, provide hydroelectric power, and to develop programs for soil erosion control and reforestation for the rural Southeast.

More recently, the national interest in rivers has evolved to include protecting the quality of river systems and their use by aquatic and riparian species, as demonstrated by the passing of the Wild and Scenic Rivers Act, the National Environmental Policy Act, the Clean Water Act, and the Endangered Species Act. The Wild and Scenic Rivers Act (16 U.S.C. 1271-1287) was passed in 1968 to protect the free-flowing character of certain rivers that were selected for having exceptional wild, scenic, or recreational values. In 1969, the National Environmental Policy Act established a national framework for protecting our environment, including its freshwater systems (42 U.S.C. s/s 4321 et seq.). Today, the environmental impact assessments of proposed infrastructure projects are integral to the public debate surrounding new development. The nation passed the Federal Water Pollution Control Act Amendments of 1972, commonly known as the Clean Water Act (CWA) (33 U.S.C. 1251 et seq.) as a response to river contamination. Since the act was passed, the fraction of the nation's rivers considered "swimmable and fishable" has increased from one-third to two-thirds, and the number of people served by secondary wastewater treatment has more than doubled (http://www.acnatsci.org/education/kye/pp/kye102002.html). In 1973, the Endangered Species Act, which called for the identification of our nation's threatened and endangered species, was passed and has since provided mechanisms for acquisition and maintenance of "critical habitat" for these species (7 U.S.C. 136; 16 U.S.C. 460 et seq.).

Despite the many federal initiatives designed to protect rivers, gaps in our scientific understanding of river processes often limit our ability to manage rivers effectively. With human population growth, the demand for river goods and services is increasing, while recurrent drought, floods, and climate change raise concerns about the sustainable use of river systems in the future (Postel et al., 1996; Vörösmarty et al., 2000; Poff et al., 2003). Furthermore, human impacts on the landscape have reached unprecedented levels, and now rival the forces of nature in their effects on rivers. Today, the multiple, sometimes incompatible services we demand of rivers and their riparian corridors and watersheds have led to conflicts among the many beneficiaries of river services (Baron et al., 2002; Naiman et al., 2002). Difficult policy and management decisions about river functions increasingly require the integration of science-based information that crosses traditional scientific disciplines. To better inform decision making, managers and policy makers seek input from science on how river systems would likely respond to policy and management alternatives. Providing the science-based information to support these management decisions demands renewed commitment to an interdisciplinary scientific synthesis, a river science, focused on rivers and how they function.

WHAT IS RIVER SCIENCE?

Ordinarily treated the river is like the veins of a leaf;
broadly viewed it is the entire leaf. W. M. Davis

Although the term "river science" is not well established, it is used now with greater frequency to describe *the study of processes affecting river systems*. River science is an emerging interdisciplinary endeavor integrating biology, geology, chemistry, and the fluid mechanics and physics governing water and sediment transport. It includes the study of how physical, chemical, and ecological processes interact to influence the form and dynamics of riverine ecosystems and how riverine ecosystems in turn influence these processes across multiple spatial and temporal scales.

River science seeks to understand and develop a predictive framework for the linkages between fluvial and ecological processes and patterns at multiple scales. This framework should inform our understanding of river systems across gradients from small streams to large lowland rivers, from pristine watersheds to heavily urbanized or managed watersheds, and from short-term dynamics to decadal- or century-scale dynamics. Because rivers are networks with longitudinal, lateral, and vertical linkages, the science of rivers includes the study of the linkages between watersheds, riparian zones, floodplains, groundwater, headwaters, and downstream navigable rivers.

Given the high degree of interdependence among a river's physical, biochemical, and ecological systems, river science is naturally an interdisciplinary scientific enterprise. For example, floods mobilize channel-bed sediment while depositing silt and clay locally in floodplains. At the same time, flooding and sediment deposition provide new, if transient, habitat for wetland species while also potentially disrupting the life cycles of some upland species. Further, during a flood, the rate of nutrient processing in the channel and hyporheic zone (the subsurface interface between groundwater and surface water) changes according to modifications of channel geometry and streambed topography.

A full review of the major hydrologic, ecological, geomorphological, and biogeochemical processes important to river science is beyond the scope of this report. The reader is encouraged to consult the many excellent existing texts on these subjects (e.g., Brutsaert, 2005; Allen, 1995; Bridge, 2003; and Drever, 1997, respectively). However, graphical summaries of some of the key processes are shown in Figures 1-1a through 1-1d. These figures are also useful to visualize how rivers may be seen from the disciplinary perspectives of hydrologists, geomorphologists, biogeochemists, and ecologists.

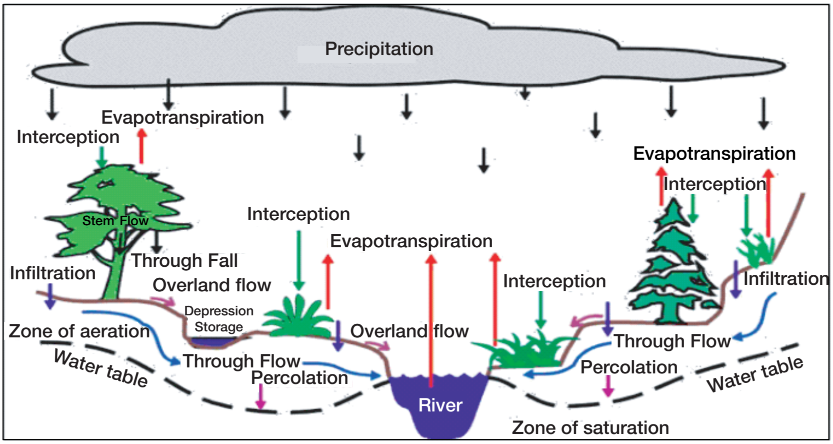
While this report distinguishes between watershed science, which encompasses a broad range of human activities within watersheds, and the more narrowly defined river science, the social sciences play a direct role even in the latter. For example, the extraction of water from rivers or their floodplain sediments for human uses may alter hydrographs, influence sediment transport, and directly impact stream ecosystems. Economic or sociology may be incorporated into stream restoration science. Cultural geography may also have direct application to river science research.

River science not only spans multiple disciplines but also multiple spatial and temporal scales. Watersheds range in size from under a square kilometer to hundreds or thousands of square kilometers, and the physical and biological environment changes as a river travels from its headwaters to its outlet. Along this flow path, riverine units, such as reaches, orders, and subwatersheds, are linked in a nested hierarchy. Riverine processes inherit these hierarchical relationships. For example, small-scale or short-term physical processes may influence reach-scale habitat features that in turn mediate ecological processes at much broader scales and over longer time periods. Thus, river science analysis at multiple scales is often required to provide knowledge needed for predictive frameworks and to inform management and restoration decisions.

Because river science studies must include the spatial and temporal scales of operation that are relevant to the problems at hand, studies vary dramatically. For example, to assess how local fish populations might be affected by the deepening of the navigational channel of the lower Mississippi River, fish habitat studies might reasonably be confined to this stretch of river. In contrast, examining how sediment fluxes from the Mississippi River to the Gulf of Mexico have changed with time involves looking at potential sediment sources and transport processes throughout the entire river basin.

Because of its interdisciplinary focus on the physical, chemical, and biological processes affecting the stream channel, floodplain, and riparian corridor

a. Hydrology



b. Geomorphology

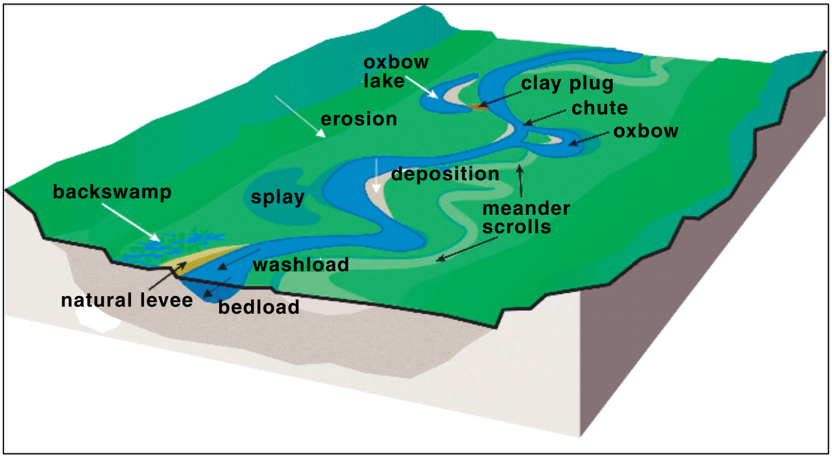
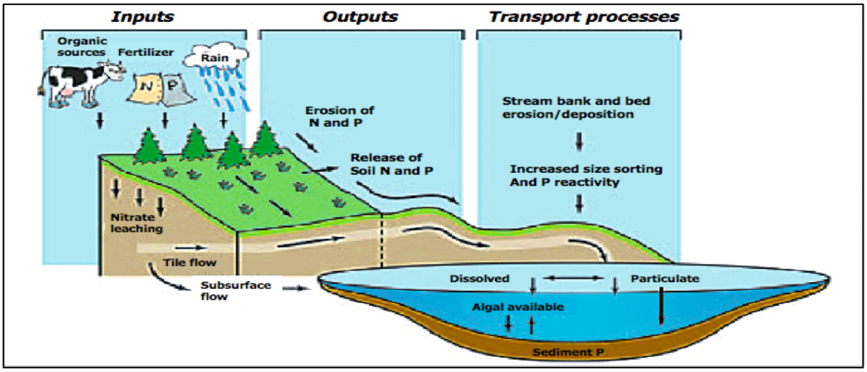
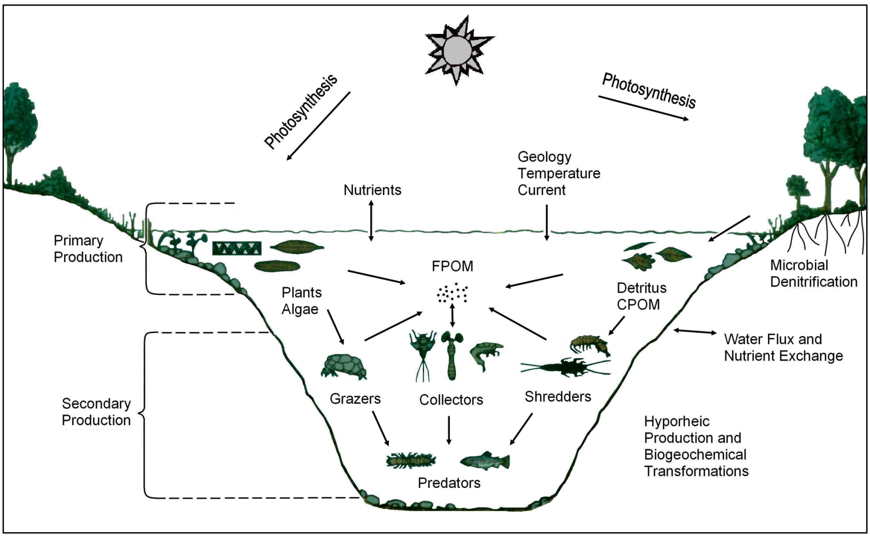


FIGURE 1-1 Four disciplinary perspectives of rivers from (a) hydrologists, (b) geomorphologists, (c) biogeochemists, and (d) ecologists. SOURCE: (a) ga.water.usgs.gov/edu/charts/water distribution.gif, (b) modified from http://www.epa.gov/watertrain/ecology/ecology18.html, (c) modified from http://www.epa.gov/watertrain/pdf/issue3.pdf, and (d) modified, with permission, from Cushing and Allen (2001). © 2001 by Elsevier.

c. Biogeochemistry



d. Ecology



through which the river flows, the domain of river science is not constrained by any arbitrary spatial scale or boundaries defined by the morphology of channels, floodplains, or terraces. Rather, the domain and bounds of river science are defined by the process bounds and characteristic spatial and temporal scales that are necessary to realize a predictive understanding. This interdisciplinary, process-based, multiscale approach to studying rivers distinguishes river science as an appropriate and increasingly valuable approach for supporting policy-relevant decision making for the nation.

THE USGS AND RIVER SCIENCE

The USGS's mission to "serve . . . the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life" (http://www.usgs.gov/aboutusgs/) suggests it is well positioned to play a key role in the future of river science. As the primary science agency of the Department of the Interior, the USGS has a responsibility to assist society in addressing science issues associated with rivers. The nature of the USGS as a national and nonregulatory agency enables the USGS to provide "policy relevant and policy neutral" information and understanding. In addition, river science spans traditional scientific disciplines where the core strengths of the USGS lay—hydrology and hydraulics, sediment transport, biology and ecology, aquatic chemistry, hydroclimatology, geology, and resource mapping. As such, the USGS is uniquely positioned among federal agencies to draw from the disciplinary expertise throughout its organization to provide needed integration and synthesis. This potential is highlighted in numerous reports including the NRC reports *Research Opportunities in Geography at the U.S. Geological Survey* (NRC, 2002a) and *Assessing the National Streamflow Information Program* (NRC, 2004d).

ADDRESSING THE STATEMENT OF TASK

The NRC's Committee on River Science at the U.S. Geological Survey was asked to provide guidance and advice for the USGS's vision for river science, in accordance with its statement of task presented in Box 1-1. This report contains the results of that study. Within Box 1-1 we highlight the chapters that address the particular tasks given the committee by the USGS.

The committee addresses the first task (i.e., to identify the highest priority river science questions for the USGS) in Chapter 4. This chapter proposes three topical areas for special emphasis, namely, environmental flows and river restoration, sediment transport and geomorphology, and groundwater and surface-water interactions. It also recommends two crosscutting science activities, namely, surveying and mapping the nation's river systems according to key physical

BOX 1-1
Statement of Task

The NRC will provide guidance and advice to the USGS on the following issues:

1. Of the many river science questions, which should be a high priority for the USGS given its unique capabilities and limitations compared to other agencies (Fish and Wildlife Service, Corps of Engineers, Bureau of Reclamation, etc.), academia, and the private sector? *(Chapter 4)*
2. Which hydrologic, geomorphic, chemical, and biological variables should the USGS monitor to provide the information needed to address river science issues? *(Primarily summarized in Chapter 5, "Integrated Data Collection and River Monitoring")*

What are the new opportunities and challenges in measurement technology that should be developed and applied to River Science issues? *(Chapter 5)*

What additional benefits could be achieved through a higher degree of integration of river monitoring activities including flow, sediment, chemistry, and biota? *(Primarily Chapter 5, "Establishment of Reach-Scale Monitoring")*

Monitoring for purposes of improved understanding and regional characterization often emphasizes network designs that maximize spatial coverage with minimal temporal coverage. What scales need to be applied to spatial and temporal coverages to capture changes in principal hydrologic, ecologic, and chemical components of complex river systems? *(Chapters 4 and 5)*

In what ways do the USGS databases, spanning multiple disciplines, need to be modified to adequately store, manage, and disseminate River Science data in useful ways? *(Chapter 5, "Integrated Data Archiving, Dissemination, and Management")*

3. What should be the underlying design principles behind USGS River Science research? *(Chapters 4, 5, and summarized in Chapter 7)*

What are the appropriate temporal scales (years versus decades) and spatial scales (single site, short reach, small watershed, major basin) that should be employed in USGS river science studies?

What should be the balance between intense studies of individual systems, and broader regional or national studies?

Where should most of this work take place (e.g., small, fairly pristine streams; moderate to large rivers which are significantly affected by land uses such as agriculture and urbanization; or large, highly modified rivers)?

and landscape features, and expanding work on predictive models, especially those that simulate interactions between physical and biological processes.

Most of the second task (i.e., to identify key variables to be monitored and data-managed) is addressed in Chapter 5. Table 5-1 summarizes some key recommended variables. The chapter proposes enhancements in streamflow, biological, and sediment monitoring; these include establishing multidisciplinary, integrated reach-scale monitoring sites and developing a comprehensive national sediment monitoring program. It also encourages the USGS to be at the forefront of new technology application, including airborne lidar and embedded, networked wireless sensors.

The answers to most elements of the third (which asks the committee to balance temporal and spatial scales, local intense studies vs. broad regional or national studies, and work on small, pristine streams vs. large, heavily impacted rivers) are topic specific. Thus, they are different for each individual recommendation. Establishment of the recommended reach-scale monitoring sites, and increased work in groundwater and surface-water interactions, imply local intense study of processes. In contrast, recommended river surveying and sediment monitoring programs would be national in scale and might last for many decades or even centuries. Overall, most of the recommended research areas, such as stream restoration, environmental flows, and models that predict ecological change, imply considerable work in highly altered rivers. However, most of these would benefit from and may require comparative sites in more pristine environments. Thus, the committee defers the details of this task to the USGS pending how it chooses to organize its scientific disciplines to most effectively address river science issues (see Chapter 6).

REPORT ORGANIZATION

The overall organization of the report is as follows. Chapter 2 first frames the broad societal issues that provide purpose for river science questions. That is, what are current challenges that make learning more about the science of rivers important? Chapter 3 describes the range of entities involved in river science, from the USGS and other federal agencies to state governments and nonprofit agencies, and details the unique role of the USGS in river science research. Then, with society's needs, existing activities, and the USGS's unique qualifications as a context, Chapter 4 outlines five important science priority areas the USGS should investigate to best be able to address key river science questions. Chapter 5 looks at the river monitoring and data management infrastructure that supports existing activities in river science and management and recommends an approach to handling the diversity of information and data needed to support the science priorities. Chapter 6 addresses how interdisciplinary river research might be augmented and coordinated at the USGS. Finally, Chapter 7 presents the committee's conclusions and recommendations.

2

Major River Science Drivers and Challenges

The nation faces many complex challenges in its stewardship of natural resources. Human landscape alterations over the last few hundred years have significantly changed the form and functioning of river systems. Population and economic growth have dramatically increased the competing demands for limited river-based services that are central to the growth and health of the nation's economy and quality of life (including water supply, navigation, recreation, flood control, and hydroelectric power). Simultaneously, expectations to maintain and restore the natural functioning of the nation's river ecosystems are increasing. Indeed, trade-offs between the impacts on ecosystems, sustainable allocation of water resources, and economic interests are often at the center of regional and interstate management problems. Furthermore, innumerable rivers flow through federal lands (such as the national parks, national forests, wildlife refuges, and military bases) and thus the government also has a legal interest in river policy and management. Current projects such as restoring the Florida Everglades and Pacific Northwest fisheries, decreasing Mississippi-Gulf hypoxia, and minimizing the impacts of urbanization on streams and rivers, reflect a pervasive national need for science-based information to support policy and management decisions that affect the nation's rivers.

The impact of human landscape alterations on the valuable goods and services rivers provide have given rise to public policy debates about how rivers should be optimally managed, debates that would benefit from science-based information. Humans have utilized rivers for centuries, and in the process have altered their form and function. These alterations have, however, become so pervasive they are having *cumulative impacts* that society can no longer ignore. Historically, the incremental effects of human activities on rivers have been managed as *de minimis* local perturbations. Yet from the ubiquitous presence of pharmaceuticals in natural waters to the wholesale diversion and consumptive use of water resource systems, the cumulative impacts of local management decisions have surpassed anticipated consequences. Furthermore, they confound the traditional management frameworks that guide policy and management decisions. Therefore, the national need for a new integrated multidisciplinary river science is more compelling now than ever before.

Within this chapter, we explore these challenges that are driving our current policies and management practices and thus our need for river science: ecological restoration (including dam removal), relicensing of hydropower facilities, invasive species, water allocation, climatic variability, urbanization and other land-use changes, and water quality. We also mention briefly the economic value of river ecosystem services, a matter that is particularly relevant when the case for river science is rationalized based on the values rivers provide. We conclude with an outline of the characteristics that river science needs to have to confront the individual unmet challenges and overall cumulative effects that human activities have on river ecosystems.

ECOLOGICAL RESTORATION AND DAM REMOVAL

Human and natural actions have caused the loss or degradation of riverine habitat. Throughout the country, thousands of ecological restoration efforts are being undertaken to improve water quality, manage riparian zones, improve habitat, and stabilize streambanks (Bernhardt et al., 2005). Billions of dollars are being spent on small projects including an Ecosystem Initiative on the Platte River (Box 2-1) and billions more on major restoration projects in the Everglades, coastal Louisiana, the California Bay and Delta, and the upper Mississippi River. Yet the science of river restoration is still in its infancy.

Dam removal is a high-profile form of river restoration. Because dams with significant storage capacity dramatically alter riverine flows—creating lakes where rivers once flowed and fundamentally altering the downstream flow regime—they have had enormous impacts on ecological patterns and processes in rivers. Currently in the United States, the National Inventory of Dams lists 76,000 dams that exceed 2 meters in height and estimates 2 million more of less than 2 meters in height (Graf, 1999; http://crunch.tec.army.mil/nid/webpages/nid.cfm). For many of these dams, their original uses have long disappeared and they stand only to hold back river water and are thus a repository for collecting river sediments, nutrients, and contaminants. Almost 500 dams were removed during the 20th century, most of which were less than 5 meters in height (Poff and Hart, 2002). Removal of these small dams has been accelerating in recent years as their economic viability declines, dam owners realize their increasing legal and financial liabilities, and the government recognizes the environmental benefits of their removal.

BOX 2-1
Restoration of Biological Habitat:
The Platte River, Central Nebraska

Braided reaches of the Platte River in central Nebraska provide important habitat for migratory and nesting birds, including three endangered or threatened species: the whooping crane (*Grus americana*), the northern Great Plains population of the piping plover (*Charadrius melodus*), and the interior least tern (*Sterna antillarum athalassos*) (NRC, 2005). Further to the east, the Platte River provides habitat for the pallid sturgeon (*Scaphirhynchus albus*), which is also endangered. A considerable amount of the riverine and wetland habitat available to these species prior to human settlement has now been lost or altered. Much of this loss can be attributed to changes in streamflow hydrology caused by reservoirs and water-diversion systems, some of which lie far upstream of the areas of interest.

The USGS has been involved in hydrologic studies of the Platte River system for many years. The current effort—known as the *USGS Platte River Ecosystem Initiative*—involves all four disciplines within the USGS (Biological Resources, Geologic, Geographic, and Water Resources). Its objectives are to (1) provide a better understanding of migratory and resident birds and the ecology of their habitats and of the physical processes that influence these habitats, and (2) use this knowledge to evaluate the effects of different management strategies on individual species and habitats (http://mcmcweb.er.usgs.gov/platte/index.html). The initiative includes eight project elements, each targeting specific concerns or questions regarding the hydrology and/or ecology of the Platte River system. Collectively this work will improve the understanding of linkages between hydrology, geomorphology, biological communities, and ecosystem processes, which can then be used to develop strategies to sustain or rehabilitate the riparian ecosystem of the central Platte River.

However, the loss of the benefits associated with a dam together with the costs of removal must be balanced against the benefits created by the removal. This requires an understanding of the river system's likely response to dam removal. The sediment accumulated behind the dams, which may contain toxic materials, must be considered and plans made either for its disposal or to address the effects of its movement into the downstream channel. If restoration of aquatic habitat is a goal, how will this be accomplished and what other actions will this restoration require? How does one measure or assess the benefits of the removal? Even at dams that are no longer in use, the overall costs and benefits and impacts of removal must be developed. The science to support these analyses is in its infancy and limited by the small number of case studies (see Boxes 2-2 and 2-3) where dam removal has been followed by adequate monitoring.

Among scientific and many practitioner communities, there is a strong consensus that this restoration should be by adaptive iteration—try an approach, monitor to see how it works, and then adjust if necessary. However, legal and

BOX 2-2
Dam Removal:
The Elwha and Glines Canyon Dams, Washington

The proposed plan to dismantle the Elwha and Glines Canyon dams on the Elwha River in the Olympic Mountains, Washington, represents the most ambitious dam removal project in the United States. Authorization to remove these two dams comes from the Elwha River Ecosystem and Fisheries Restoration Act, passed by Congress in 1992 to restore the natural system. As the name of the act implies, the primary purpose of dam removal is to restore the ecosystem and native salmon fisheries of the Elwha River system. This "natural" system restoration goal implies a state that is often difficult to define because of natural variability and a lack of ecosystem information prior to dam construction. USGS scientists have played important roles in evaluating the potential impacts of dam removal in two key areas: (1) assessing the fate of the sediment stored behind the dams and (2) assessing the suitability of in-channel habitats and water-quality characteristics for restoring ecosystem processes.

During a lake drawdown experiment in 1994, USGS hydrologists made bed load and suspended load measurements in the vicinity of a delta formed at the head of the upper reservoir (Lake Mills) to evaluate the potential mobility of sediment stored behind the dams (Childers et al., 2000). The results of that work were used to develop a sediment transport model for managing the movement of sediment into and through the channel reach downstream of the dams.

In a related study, USGS hydrologists collected baseline data to assess nutrient concentrations and habitat characteristics throughout the basin (Munn et al., 1999). They found that nutrient concentrations were quite low (often below detection limits) suggesting that nutrients from salmon carcasses brought into the system by the salmon's natural life cycle would greatly benefit the ecosystem if additional instream habitat were restored. They also found that, while most of the tributary channel network is very steep (> 16% slope) and unlikely to provide much spawning and rearing habitat, the main stem of the Elwha River upstream of the dam contains large areas of potential habitat.

logistical issues often discourage such an approach. Often funds are available only for a short period of time or for a single restoration action. Further, because the majority of these projects have had little or no monitoring after restoration activities, we know little about which restoration approaches are most effective or even if projects are completed as designed (Hassett et al., 2005).

Research on how best to measure restoration effectiveness and how to quantify multiple river ecosystem services in meaningful ways is critical. Palmer and Allan (2006) recommended that a coordinated national study evaluating the effectiveness of different restoration approaches, particularly those that are expensive and highly interventionist (e.g., channel reconfiguration projects) be com-

BOX 2-3
Dam Removal:
The O'Shaughnessey Dam, Hetch Hetchy Valley, California

O'Shaughnessey Dam that floods the Hetch Hetchy Valley, California, has been controversial for the past 100 years. It is the only major dam built in a national park and was strongly opposed by John Muir, who compared the Hetch Hetchy Valley in beauty and uniqueness to Yosemite Valley. Despite the opposition, San Francisco has managed to maintain its hold on Hetch Hetchy because of scarcity of water supplies in northern California. The removal of O'Shaughnessey Dam and the restoration of the river and the valley have received serious consideration because of two studies that show that with optimal use of other dams in the region, the 250,000-acre-foot-capacity dam could be removed with only a minor loss of 20,000 acre feet of water (Null, 2003; Rosekrans et al., 2004). In addition, the recreational pressure in Yosemite Park is very high, especially in the valley. Demand for recreation in a parallel valley in future years would clearly add to the economic base of the region. There will be additional costs from the removal of O'Shaughnessey Dam, primarily due to the loss of hydropower and the need for substantial additional treatment of San Francisco's water if stored in downstream dams.

The sediment disposal problem that hinders many dam removal proposals is minor in this case, as the largely granitic High Sierra catchment has yielded very little sediment over the past 90 years. There are even plans to replace the original trees by identifying their stumps if they become exposed. Surveys during the last major drought showed the feasibility of this restoration.

However, the debate on the removal of the dam has moved from one about water and scarcity to one that pits the interests of the City of San Francisco against those of the local regions around Hetch Hetchy that would benefit from continued growth in the tourist trade. Since very little water is lost, these impacts can now be assessed on a purely financial basis, taking into account the environmental benefits from a Hetch Hetchy restoration. In the long run, given the increase in the scarcity value of prime recreational sites, and the ability to effectively store water elsewhere, the removal of the dam is likely. Additional information on the impacts to the river environment and other effects from the removal of the dam by the USGS would provide a reference against which the optimal interests of the nation in this case could be judged.

pleted and that the USGS was poised to undertake such research. Other research frontiers include determining how best to restore ecosystem processes under highly constrained conditions that surround dams and levees or in urban settings, how to move some aquatic ecosystems beyond "restoration" to boost their ability to perform functions of value to society, and how to identify feedbacks associated with critical thresholds beyond which river restoration is not possible (Palmer and Bernhardt, 2006).

RELICENSING OF HYDROPOWER FACILITIES

Hydropower dams are a source of considerable discussion because they are subject to periodic relicensing by the Federal Energy Regulatory Commission (FERC). In the relicensing process, dam operators must discuss, among other things, the impact of their operations on the riverine environment and steps, if any, they will take to mitigate negative impacts. Citizen groups and environmental nongovernmental organizations frequently raise questions about these impacts and ask why the dams should not be removed or have their operations modified. Many of the questions center on the timing and volume of releases from the structures and the impact these have on water quality and instream habitat and aquatic species below the dams. As with dam removal, these questions rest on knowledge of the present state of the river and the ability to predict future conditions. Over the years, approaches for modeling habitat changes downstream of dams have evolved from relatively simple measurements of minimum wetted habitat for select aquatic species to more complex analyses. These more involved analyses consider how the altered flow regime modifies the normal distribution of high and low flows and investigates how the flows influence a much broader suite of species and affect the entire aquatic ecosystem. Still more work is needed to gain a predictive understanding of the linkages between flow variations and river habitat in highly regulated rivers.

INVASIVE SPECIES

Deliberate and unwitting human actions have brought thousands of alien invasive species to this country and spread them across the aquatic and terrestrial landscape. Saltcedar has infested watercourses throughout the western United States, causing declines of native riparian trees, and is now the object of a multimillion-dollar eradication campaign (Morisette, 2006) (Box 2-4). The Asian carp, originally brought to this country with government approval to clean the beds of southern catfish farms, escaped and now threatens fisheries in the Mississippi and Illinois Rivers and possibly the Great Lakes (Kolar and Lodge, 2002). The zebra mussel, which infests the Great Lakes and major rivers such as the Mississippi and Ohio, has cost municipalities, utilities, and the fishing industry billions of dollars.

These and thousands of other plants and animals species have entered the country attached to packing crates, interspersed with agricultural imports, or in the ballast discharged into our ports and harbors. Insufficient knowledge exists about how these species spread and, therefore, how they can be eradicated or, more plausibly, how their spread can be limited (International Joint Commission, 2004). These exotic species often flourish in highly altered river ecosystems. Therefore, much thought needs to be given to how river and riparian restoration can be used to minimize the success of these exotics, and how much restoration is needed to accomplish a given level of reduction.

BOX 2-4
Invasive Species:
Tamarisk Invasion in the Western United States

Riparian areas bordering streams and rivers in arid regions of the western United States have been profoundly changed by the invasion of non-native plants, such as Eurasian saltcedar or tamarisk (*Tamarix ramosissima*). Since its introduction in the 1800s, Tamarisk is now the third most common woody riparian plant species in western river ecosystems in North America (Friedman et al., 2005). Comparisons of early and modern-day photographs of floodplains and riparian segments of semiarid streams illustrate vividly how native plants such as sandbar willow (*Salix exigua*) and Fremont cottonwood (*Populus fremontii*) have been completely replaced by tamarisk.

In the 1960s, the USGS initiated field studies on rivers throughout the western United States to evaluate the role of tamarisk and other phreatophytes in cycling water through riparian areas. The results indicated that floodplains covered with mature tamarisk can transpire 1-3 meters of water per year (Weeks et al., 1987), which far exceeds annual precipitation rates. In contrast to native riparian plants, tamarisks have a high leaf area index (leaf area per unit of ground area); thus, they are highly efficient in cycling water between the land surface and the atmosphere (Shafroth et al., 2005).

More recently, USGS scientists at the BRD Science Center in Fort Collins, Colorado, have been examining interactions among streamflow, fluvial geomorphology, and riparian vegetation, including environmental factors that favor non-native plants such as tamarisk (http://www.usgs.gov/invasive_species/plw/). One such project uses data and information from 500 long-term gaging stations in 17 western states. Data from these sites will be used to relate the abundance of native and non-native woody riparian plants to the timing and magnitude of streamflow, channel geometry, salinity, and climate. The long-term objective of this work is to identify the factors influencing the current distribution of native and non-native plants and provide resource managers with information and tools for predicting the spread of non-native species.

Research on the life history characteristics of the invaders and how to predict the rate of their spread as a function of river hydrology and network configuration is critical. This should be coupled with research on the consequences invasive species have on river biodiversity and ecosystem processes.

WATER ALLOCATION AND REALLOCATION

Recently, five years of severe drought in the western United States brought attention to the allocation of water among water users. Forecasts that the drought might have continued and would have required a reallocation of the waters of the Colorado River heightened political attention to allocation issues. Coupled to large-scale issues, such as those of the Colorado River, are numerous other conflicts over the allocation of flows in smaller streams. Efforts to protect the silvery minnow in the Rio Grande River through directed low flows led to years of lawsuits with the City of Albuquerque and the Albuquerque-Bernalillo County Water Utility Authority, who were concerned about maintaining a reliable water supply. Similar efforts are also underway in the Klamath Basin in Oregon where agricultural interests are in conflict with the government over the need to provide flows for the threatened and endangered species in the lakes and rivers (suckers and coho salmon). In this case, an NRC study concluded that the scientific information available to make these decisions was scarce, and so in its absence, resource managers were forced to rely more heavily on their judgment and follow the precautionary principle in prescribing flow requirements (NRC, 2004b).

While many water allocation conflicts are concentrated in western states (Box 2-5 provides another example), they are becoming more common in the east as well. Periodic drought combined with rapidly growing urban areas has led to conflicts in major river basins, such as the Apalachicola-Chattahoochee-Flint (Box 2-6) and the Potomac.

Some of the research needed to address such issues is not, strictly speaking, river science, but rather involves water-use practices (e.g., conservation, conjunctive use of groundwater and surface water, water reuse). However, a better understanding of the habitat needs of species throughout their life cycle and the

BOX 2-5
Water Allocation and River Restoration:
The San Joaquin River, California

The San Joaquin River, the second longest river in California, has been the focus of a recent water allocation controversy. When the Friant and Millerton Dam came online in the 1950s, the flow in the river was reduced substantially, and a once thriving salmon run became extinct. Recently, a coalition of 13 environmental and fishing groups (http://www.nrdc.org/media/pressreleases/040827.asp) acquired a court order to restore water in the San Joaquin River to quantities sufficient to support a salmon run. The suit has been in the courts since 1988. Currently, there is a wide divergence of views on how much water would be needed, ranging from about 200 to 500 KAF (1000 acre feet, 1 KAF = 1.2335 million cubic meters). In addition, the methods with which flows can be restored in the river differ widely. Proponents of restoration claim the majority of flows can be obtained by more efficient operation and conservation in the river basin. Opponents contend that increase in flows can come only by the reduction of irrigated croplands, which consequently would have a high cost in foregone production and associated job loss.

An impartial source of technical information on flow requirements needed to restore the fishery would help resolve this difficult water allocation problem. A multidisciplinary assessment of the amount and timing of releases, the amount and quality of the habitat that could be created, and the response of salmon to these conditions is needed to assess management alternatives.

BOX 2-6
Water Allocation and Urban Growth: Atlanta, Georgia, and the Apalachicola-Chattahoochee-Flint Basin

As populations grow and consumptive use of water increases, concerns of water shortages, which have long been common in the western United States, are becoming increasingly common in the east. In Atlanta, Georgia, the population has more than tripled in the last 50 years and demand for water is expected to increase by 50 percent by 2020. Most growth is occurring north of the city center, where suburban developments with large lawns, water-thirsty plants, and swimming pools are increasing. Atlanta's residents share water from the Apalachicola-Chattahoochee-Flint (ACF) river basin with residents of Alabama and Florida. Multiple stakeholders throughout the region all lay claim on river waters, including navigation interests, hydroelectric power generators, and industrial water users. Additionally, for ecological purposes Florida residents have been proponents for maintaining natural flow regimes.

As of early 2006, many streams and rivers in the basin are flowing at less than half their usual rate (http://water.usgs.gov/waterwatch/). Therefore, reservoir levels are dropping, and "water wars" have arisen between hydroelectric power interests, lakeside homeowners, water recreation enthusiasts, and residents who rely on the reservoirs for drinking water. Drought conditions have further exacerbated the problems and have led to emergency restrictions on water use. New water- and land-use policies are expected in the coming decade.

The environmental implications of these water problems and thus the most effective policies are, however, still unclear. These issues are well suited for an interdisciplinary science approach, as is the development of scientific solutions for increasing the efficiency of water distribution systems that allow for protecting ecological water needs while meeting human needs.

relationships among habitat, hydrology and hydraulics, geomorphology, and other characteristics are key to providing the scientific foundation for evaluating the ecological consequences of flow management decisions.

CLIMATIC VARIABILITY

The ecological and sociological impacts of climatic variability have been and will continue to be significant on seasonal, annual, and decadal timescales. While there may not be complete agreement on the anthropogenic contribution to climate change, the evidence of significant climate variation both from the modern instrumental record and from historical reconstructions from tree rings and other paleoclimate data is indisputable. Streamflow variability in the western United States is strongly tied to large-scale interannual and interdecadal climate oscillations (Redmond and Koch, 1991; Kahya and Dracup, 1993; Dracup and Kahya, 1994); low-frequency streamflow variations over the last 500 years have also been shown to be related to large-scale climatic variations in the

Pacific and Atlantic Oceans (Hidalgo, 2004). Reduced rain or snowfall (e.g., Mote et al., 2005) or changes in snowmelt timing (Box 2-7) can severely impact agricultural production and threaten to increase conflicts over scarce water resources. Conversely, in other parts of the United States, observed increases in heavy precipitation events in recent decades (Karl and Knight, 1998; Kunkel et al., 1999; Groisman et al., 2001) might increase flooding in those areas. Climatic variability changes the flow regime of river systems, which is a "master variable" controlling river geomorphology and ecology (Poff et al., 1997). For instance, the temporal sequence of floods can affect the configuration of the river channel and floodplain (Schumm and Lichty, 1963). In the arid Southwest, episodes of channel down-cutting are associated in part with changes in the fre-

BOX 2-7
Climatic Variability:
Earlier Snowmelt in the Western United States

The hydrologic response to climate change in the 21st century may be most apparent in western mountains. Historical streamflow records for the western United States indicate that the timing of the snowmelt spring pulse is earlier by about 10 days than in previous decades (Regonda et al., 2005; Stewart et al., 2005). The trend is widespread throughout the Sierra Nevada. Timing changes are related to long-term warming trends during the winter and spring across the western United States (Dettinger and Cayan, 1995). Warming in mountainous areas affects not only the timing of the spring melt but also the partitioning of precipitation into snow or rain. In catchments sensitive to changes in this partitioning, such as the American River, changes in the frequency of floods have also been observed (NRC, 1999a).

Although large-scale interannual and interdecadal climate variations related to the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) account for part of the streamflow trends, climate change during the late 20th century is also significant (Stewart et al., 2005). Projected changes in climate over the 21st century predict a climate that would result in greater shifting in seasonality of streamflows, with more precipitation as rain, more frequent flooding, earlier loss of mountain snowpack, and lower summer and autumn baseflows (Dettinger et al., 2004; Knowles and Cayan, 2004). Given the sensitivity of snow-fed western mountain rivers to air temperature and precipitation variability, the impact of large-scale climate change would be significant in this region.

Understanding and predicting the impacts of climatic variability and change on river flow regimes and flood frequencies is only one of the challenges. A changing hydrologic regime would also put a greater strain on water resources management. In the western states the competition for water is already intense and is represented by numerous users with interests in both consumptive and nonconsumptive water use. Recorded variations in flows representing climatic conditions of the recent past will be insufficient to guide decisions on future operations. A science-based understanding of climate changes and their impacts on watershed hydrology will be needed to manage water resources during the 21st century.

BOX 2-8
Climatic Variability: Trends in High and Low Flows

Concerns over the hydroclimatic effects of climate change have led to widespread speculation that increases in temperature may accelerate the hydrologic cycle, producing more extreme floods and severe droughts. USGS hydrologists Harry Lins and Jim Slack (1999) examined this by studying trends in streamflow in the conterminous United States during the 20th century. They used historical records from 395 climate-sensitive gaging stations to evaluate differences in high, medium, and low flows; each of the stations had continuous daily records from 1944 to 1993 (50 years), and 34 had records of 80 years or more.

Results showed that since the 1940s, values of annual minimum to median flows have generally been rising throughout most of the United States; the number of stations with upward trends in low flows is much higher than the number exhibiting downward trends. However, there has been little change in high flows. For annual maximum daily discharge, only 35 stations showed a significant trend, and these were roughly balanced between positive and negative trends. Increases tended to be in the East and upper Midwest; decreases were scattered throughout the country. McCabe and Wolock (2002), using 400 sites in the conterminous United States measured during 1941-1999, reached similar conclusions, but found a "step" increase in annual minimum and median daily streamflow around 1970, followed by stabilization of the new regime.

Long-term trends for the western United States may, however, be toward lower overall discharge. Using an ensemble of 12 climate models to predict relative changes in runoff in the 21st century, Milly et al. (2005) projected an estimated 10-30 percent decrease in runoff in midlatitude western North America by the year 2050. Such changes in sustainable water availability would have regional-scale consequences for both our economies and ecosystems (Milly et al., 2005).

quency of large floods during the Holocene (Hereford, 2002). Variations in the magnitude and frequency of high and low flows (Box 2-8) affect the creation, availability, and quality of river habitat. Climate extremes and low flow conditions can also combine to create acute conditions for aquatic species by raising water temperatures above threshold limits. Therefore, an improved understanding of the role of large-scale climate oscillations and trends on streamflow timing and seasonality is needed.

With an improved ability to forecast short-term seasonal and interseasonal climate variations, there are more opportunities to better manage water resources for aquatic species, particularly in the context of adaptive management experiments (Pulwarty and Redmond, 1997; Pulwarty and Melis, 2001). Furthermore, a better understanding of the impacts of climate variations on riparian vegetation and river aquatic habitat is needed to implement effective restoration measures or control invasive plant species.

URBANIZATION AND OTHER LAND-USE CHANGES

Just as climatic variability inhibits our ability to rely on past conditions to develop future climate predictions, ongoing changes in urban occupancy and rural land use hinder our ability to predict future land-use impacts. The quantity and quality of river flows are tied directly to land-use activities (Allan, 2004). Seemingly minor changes in land use can create significant changes in the pattern of runoff that reaches streams and rivers. Therefore, our ability to accurately predict and manage floods or to estimate water availability is limited by our understanding of these minor changes. Current federal regulations governing flood insurance generally do not require the consideration of future conditions, although there is a movement toward including predictions of future riverine hydrology in flood stage predictions.

Changes in the quantity and quality of water because of rural land-use modifications and urbanization can severely affect downstream environmental conditions on both regional and local scales. These changes lead to habitat modifications that affect both aquatic and terrestrial species dependent on access to clean water (Moglen et al., 2004). Regional modifications in rural land-use activities have changed how the landscape regulates the flow of water to streams (DeFries et al., 2004). These regional shifts in land management have occurred throughout the 20th century. Examples include reforestation in the Southeast, changes in grazing management in the interior West, and alterations in logging practices in the western coastal states. On a more local scale, a study of lowland streams in western Washington, Booth and Jackson (1997) found the onset of aquatic-system degradation occurred at relatively minor levels of urban development (i.e., an effective impervious area in a watershed of 10 percent). Furthermore, the interactive effects of urbanization and climate change may be critical in some areas; urbanization can cause a dramatic rise in summer stream temperatures with large temperature spikes during rainstorms, which would likely be exacerbated in regions that experience more severe storms in the future.

Thus, the science community needs to develop a systematic understanding of the relationships between landscape changes, sediment fluxes, and ecosystem functions and services (NRC, 2001). To do this, one has to be able to distinguish between human-induced changes and natural variations in the water cycle; such work would include both field studies and model development (Hornberger et al., 2001). Field studies would logically include observations from watersheds for which good hydrological information is available and where land-use changes are documented (NRC, 2004d).

WATER QUALITY

Since the passage of the Clean Water Act in 1972, the water quality of the nation's waterbodies has generally improved. The Cuyahoga River no longer catches fire, the Potomac River is no longer labeled a national disgrace, and

Lake Erie now supports a sport fishery and is no longer considered moribund. The Clean Water Act is estimated to have prevented discharge of almost 700 billion pounds of pollutants per year, including over 1 billion pounds of toxic pollutants such as heavy metals, over 470 billion pounds of nonconventional pollutants such as nutrients and salts, and 220 billion pounds of conventional pollutants such as suspended solids (USEPA, 2002a).

However, the quality of our nation's water remains at risk. The Environmental Protection Agency's 2000 National Water-Quality Inventory indicated only 61 percent of assessed stream miles fully support all of their designated uses, and of these, 8 percent are considered threatened for one or more uses. In the remaining 39 percent of assessed reaches, one or more designated uses are impaired by pollution or habitat degradation. The situation is worse for lakes and estuaries; some form of pollution or habitat degradation impairs 45 percent of the assessed lakes and 51 percent of assessed estuarine waters by area (http://www.epa.gov/305b/). The primary water-quality problems include bacteria, nutrients, metals (especially mercury), and siltation. Their sources include runoff from agricultural lands, sewage treatment plants, and hydrologic modifications, such as channelization, flow regulation, and dredging (http://www.epa.gov/305b/).

This situation is made more complex by the increasing number of pollutants and the poorly understood chemical mixes that ensue, especially if they combine with other molecules in the environment to create endocrine disruptors. Increases in nutrient enrichment, hormones, and pharmaceutical products threaten our ability to identify new pollutants and to clean the waters for human, fish, and wildlife use (NRC, 2000, 2004c).

Gaps in our understanding of river water quality are numerous. Research needs include ecotoxicological studies for species of interest and contaminants of concern, studies of the fate and transport of lesser understood emerging contaminants, and investigations into the role of the hyporheic zone in transforming, adsorbing, and biodegrading these contaminants and nutrients such as nitrogen.

VALUING RIVER ECOSYSTEM SERVICES

The economic value of the different components of river science can act both as a constraint on the implementation of changes in river science policy, but more importantly, as a consistent method of comparing the social value of different river science actions. Economic approaches to valuing river ecosystem services are particularly relevant when the case for river science is rationalized based on the value rivers provide, and thus ultimately underlies all the drivers and challenges noted above. Given, however, that the USGS does not have an economic analysis capacity, and the development of one is not envisaged in the near future, we do not expand on this here but briefly address valuation methods and their challenges in Appendix A.

CHARACTERISTICS OF RIVER SCIENCE

A science that can begin to address some of the above drivers and challenges must have two important qualities. First, it must be multidisciplinary and integrative and second, it must be process-based and predictive. These qualities are discussed in the next sections.

Multidisciplinary and Integrative

In the past, much of the science needed for making policy and management decisions affecting river systems was supplied from traditional disciplinary science. For example, hydrologists provided information on flood hazards that guided management of flood-prone areas, and river forecasting models that allowed reservoir operators to make decisions on releasing flows when a flood is occurring. The work of geomorphologists on channel-forming flows guided efforts to control stormwater from urbanizing watersheds, where changes in the frequency of high flows leads to channel widening or incision. And biologists documented declines in aquatic species and birds that feed on them. The legacy of this disciplinary work continues to benefit the public in decision making today. Furthermore, advances in traditional disciplinary sciences focusing on rivers and river processes will continue to provide new insights for better management.

Yet there are needs for science-based information on rivers that cannot be met solely from traditional disciplinary approaches. All aspects of a river's physical, biochemical, and ecological systems depend upon each other. For example, floods mobilize channel-bed sediment, while depositing silt and clay locally in floodplains. Flooding provides critical, if transient, habitat for wetland and riparian species, while also potentially disrupting the life cycles of some upland ecosystem species. During a flood, the nutrient processing efficiency of the hyporheic zone (the subsurface interface between groundwater and surface water) changes according to modifications of channel geometry and bed topography.

Additionally, cumulative impacts of human alterations pose challenges traditional disciplinary science is incapable of solving. Historically, river and watershed management have focused on local-scale problems with direct cause and effect relationships. For instance, science has contributed to solving soil erosion problems at local scales through the plot-scale study of erosion, leading to the development and widespread use of conservation tillage and best management practices. Local problems of elevated nitrogen loads in streams have also been addressed through plot-scale research on manure application rates. While this research has been extremely valuable, it is insufficient to answer questions about the processes affecting sediment movement in major rivers or hypoxia in the Gulf of Mexico. Rivers integrate the multitude of spatially distributed, small-scale alterations to the landscape and waterways, and awareness of such cumulative impacts must guide the vision for river science.

Therefore, despite inherent difficulties, guiding the emergence of a distinct river science needs to be a multidisciplinary and integrative endeavor. To understand the functions of rivers and the impacts of human alterations, river science should synthesize information from biology, geology, chemistry, and the fluid mechanics and physics governing water and sediment transport at multiple scales. Thus, the greatest challenge is to determine which components of the very large number of physical, chemical, and biological parameters in a river system should be studied to evaluate most comprehensively their interrelationships.

While interdisciplinary research is not a new phenomenon, and river ecologists have long recognized the important role of hydrology and geomorphology in governing ecological processes (Vannote et al., 1980; Stanford et al., 1996; Benda et al., 2004), truly interdisciplinary work on rivers is still in its infancy. To clarify, throughout this report the term "interdisciplinary" is defined as the intentional effort to integrate across disciplines (combining both multidisciplinary and integrative); this is distinct from "multidisciplinary," which refers to the involvement of many disciplines but does not inherently imply integration.

In the last decade, we have seen increased emphasis on interdisciplinary research, with funding for this work coming from new programs established within existing outlets and agency sources. Some examples of recently established interdisciplinary programs include the National Science Foundation's Biocomplexity in the Environment Program, Environmental Protection Agency's Water and Watersheds Program, and National Oceanic and Atmospheric Administration's Climate and Global Change Program. Other proposals for developing major interdisciplinary research programs at the National Science Foundation are on the table and may soon be underway; these include National Ecological Observatory Network (NEON) and a merged Collaborative, Large-scale, Engineering Analysis Network for Environmental Research (CLEANER)–Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) observatory initiative. Many of the federal agencies involved in resource management or scientific research have likewise branched out to form interdisciplinary teams, programs, or initiatives emphasizing integrated research in hydrology, ecology, and engineering. Still, an even greater degree of interaction is needed today in the study of rivers.

Process-Based and Predictive

Changes to river systems during the last 200 years have been drastic and pervasive. The nation has evolved from an agrarian society of a few million inhabitants to a country of about 300 million of whom 75 percent live in urban areas. As noted earlier, there are some 76,000 dams greater than 2 m in height and perhaps 2 million smaller structures. Rivers in urban and suburban areas are connected to complex and sometimes aging stormwater and sewage infrastructure, making it difficult to define how water is routed to channels or even what constitutes the watershed. Overall, the channels and watershed landscapes of most of the nation's rivers have been so modified that the concept of a "natural river system" *sensu stricto* reference state may no longer exist.

Despite this difficult context, many of today's environmental policy decisions call for science-based information about the likely responses of river systems to changes in both natural forcing and human drivers. Empirical equations have helped improve the hydrological science knowledge of these responses. Generally speaking, regression-based approaches have been extremely useful in determining the likely responses within a defined context. The predictive abilities of these descriptive equations are, however, limited when the environment exceeds the normal bounds. The most challenging problems demand information about river systems' responses to future conditions that are outside the range of historical observations and experience, such as extreme events like Hurricane Katrina.

River science must, therefore, be structured and conducted to provide a *process-based* and *predictive* understanding of river systems. This understanding must go beyond methods that have commonly been used in the past to guide policy and management decisions, that is, operational or pragmatic predictions based on empirical associations such as regression relationships. Rather, these associations should be used to help uncover the processes beneath the trends. Sound policy decisions require a sufficient understanding of river systems so as to offer sound, credible, *testable* predictions of river systems' responses to new and previously unobserved forcing that could accompany climate change, excessive groundwater extractions, large-scale land-use conversion, hydrologic alterations from urbanization and stormwater management and, ironically, restoration actions designed to mitigate or reverse some of the above forcings.

CONCLUSION AND RECOMMENDATION

The understanding necessary to assess the complex changes of river systems to management alternatives will not come easily, especially in the midst of uncertainty. Therefore, there is a compelling national need for a new approach to studying rivers. River science—an emerging discipline distinct from traditional disciplinary sciences but still supported by their activities—can provide a vision for organizing scientific endeavors to address these unique challenges.

Recommendation: USGS river science activities should be driven by the compelling national need for an integrative multidisciplinary science structured and conducted to develop a process-based predictive understanding of the functions of the nation's river systems and their responses to natural variability and the growing, pervasive, and cumulative effects of human activities.

3

Overview of Federal, State, Nongovernmental, and USGS Activities in River Science

As discussed in earlier chapters, there is a national need for information on the functions and responses of our nation's rivers. There are also compelling arguments for meeting this need by developing a new integrative multidisciplinary perspective on rivers. As outlined in *The USGS and River Science* section of Chapter 1 and demonstrated in detail throughout this chapter, the USGS, given its history, strengths, and mission, is positioned to make unique contributions to the nation regarding river science. Still, the demands for river science information cannot be met by any one organization. Furthermore, the national interest in river systems involves many federal organizations that have a stake in the science. Their regulatory and management missions drive many of the needs for river science information, and their research activities related to these missions also contribute to the field. Given that the science of rivers involves so many entities—federal, state, and local agencies, tribal governments, public and private institutions, university research programs, and the public—and that river science itself encompasses so many disciplines, what specific role should the USGS play in river science?

To answer this question, we first review the ongoing activities at federal and state agencies and nongovernmental entities throughout the United States that already participate in the science and management of rivers. Then we outline the past and present work within the multiple disciplines at the USGS that relate to river science. This overview provides a comprehensive picture of the current state of river science research, and therefore suggests, from a realistic perspective, what needs to be done in the future. We conclude this chapter with a discussion of the role of the USGS in river science, specifically addressing the principles that should guide the priorities of a USGS river science initiative.

This provides an important context for Chapter 4, where we outline specific recommendations that will allow the USGS to best address the major river science challenges outlined in Chapter 2.

FEDERAL AGENCY ACTIVITIES IN RIVER SCIENCE

For each federal agency the scope and nature of its river research activities are tied to its unique mission and management roles. In a report on *New Strategies for America's Watersheds* (NRC, 1999b), the NRC reviewed in detail the involvement of federal agencies in water resources and river management. Table 3-1 summarizes the water-related responsibilities of federal agencies in 15 areas. Of these, research responsibilities were identified for eight federal agencies, with the USGS and the Environmental Protection Agency identified as having "significant responsibilities." Table 3-2 summarizes water and water-related natural resources research and development (R&D) funding for several agencies. Figure 3-1 gives a spatial representation of some of these responsibilities for a "typical" medium-to-large river basin. In this section we briefly describe some of the research activities of these federal agencies in river science topics. We also describe some activities for several agencies that were not identified as having a major research role but whose research on related topics, or management roles, would have a significant influence on the needs and directions for river science research. Our summary is not intended to be comprehensive; instead, it is meant to provide context for the unique role of a USGS river science initiative within the larger multiagency enterprise that deals with river science and management issues.

Federal Agencies with River Science Research Responsibilities

Forest Service **(U.S. Department of Agriculture)**—Manages federal "wild and scenic rivers" and national forest lands to promote watershed protection. Its R&D scientists carry out basic and applied research to study biological, physical, and social sciences related to diverse forests and rangelands. According to the Forest Service, its research plays "a key role in sustaining our nation's fisheries. For some native fishes, this is the only research program in the country with a primary focus on protecting, managing, and restoring their habitat. Research program objectives include: (1) defining habitat and ecosystem requirements; (2) identifying factors limiting populations; (3) developing methods to protect, improve, and restore habitats; and (4) developing cost-effective methods to monitor and evaluate habitats and populations." The Forest Service also conducts watershed studies to understand better how watersheds function and what processes enhance or impair the quantity and quality of water that comes from forests (http://www.fs.fed.us/research/).

TABLE 3-1 Major Water-Related Responsibilities of Federal Agencies

Agencies	oceans and estuaries	wetlands	research and dissertation data	hydropower	navigation	recreation	preservation	wildlife	fisheries	flow regimes	ecological diversity/restoration	erosion/sediment control	water quality	flood risk management	water supply
Department of Agriculture															
Farm Services Agency		○									○	●			
Forest Service		○	○			●	●	●	●		●	○	○	○	○
Natural Resources Conservation Service		●								○	○	●	○	○	
Agricultural Research Service												○	○		○
Department of Commerce															
National Marine Fisheries Service	●	○			○			○	●				○		
National Oceanic & Atmospheric Administration	●								●				●	●	
Department of Defense															
U.S. Army Corps of Engineers		●	○	●	●	○		○	○	●	●	●	○	●	○
Department of Energy															
Federal Energy Regulatory Commission				●											
Department of the Interior															
Bureau of Land Management		●	○			○		●		●	●	○	○		
Bureau of Reclamation			○	●		○		○	○		○	○	○	●	●
Fish and Wildlife Service		●	○			○	●	●	●		●		○		
Geologic Survey	○	●	●					○	○	○	●	○	○	○	●
National Park Service	○	○				●	●	●	●		●	○	○		
Bureau of Indian Affairs		○						○	○		○	○	●	○	
Department of State															
International Joint Commission		○			○			○	○				●	●	●
Other Federal Units															
Environmental Protection Agency	○	●	●			○	○	○	○	○	●	○	●		○
Tennessee Valley Authority		○	○	●	●	○		○	○	●	○	●	●	●	●
Bonneville Power Administration		○		●	●			○	●	○	●	○	●	●	●
Federal Emergency Management Agency														●	

NOTE: Circle indicates some related responsibilities; filled circle indicates significant responsibilities. SOURCE: Slightly modified, with permission from O'Connor (1995) and NRC (1999b).

TABLE 3-2 Research and Development Funding in Water and Water Related Areas, FY2004

Funding Category and Agency	2004 (millions of dollars)
Conservation and Land Management	
Forest Service (USDA)	253
Department of the Interior	79
Recreational resources	
U.S. Geological Survey (Interior)	169
Water Resources	
Department of Defense, Army of Engineers	27
Bureau of Reclamation (Interior)	9
Other Natural Resources	
U.S. Geological Survey	
Geological and Mineral Resource Surveys and Mapping	198
Water Resources Investigations	132
National Mapping, Geography, and Survey	46
Department of Commerce, NOAA	
Oceanic and Atmospheric Research	332
National Marine Fisheries Service	161
National Ocean Service	55
National Weather Service	20
National Environmental Satellite, Data and Information Service	24
All other NOAA	82

SOURCE: National Science Foundation (2004).

U.S. Army Corps of Engineers (Department of Defense)—Responsible for national flood-damage reduction activities; development, operation and maintenance of ports, harbors, and inland navigation; and as authorized, development, operation, and maintenance of water supply, ecosystem restoration, recreation activities, and regulation (e.g., permitting activity in wetlands under the Clean Water Act). The U.S. Army Corps of Engineers (USACE) monitors river conditions and conducts water resources research and development activities. To carry out its responsibilities, USACE conducts research and development activities in a number of fields related to river science. Its Engineer Research and Development Center conducts research on water-resources-related environmental issues, dredged material utilization, erosion control, sediment management, river mechanics, navigation, flood control and flood damage reduction, coastal protection, and environmental sustainability. The Hydrologic Engineering Center (HEC) conducts research, analysis and consultation for USACE in surface and groundwater hydrology, river hydraulics and sediment transport, hydrologic statistics and risk analysis, reservoir system analysis, planning analysis, real-time water control management, and a number of other closely associated technical subjects. Its HEC family of models are in wide use within the United States

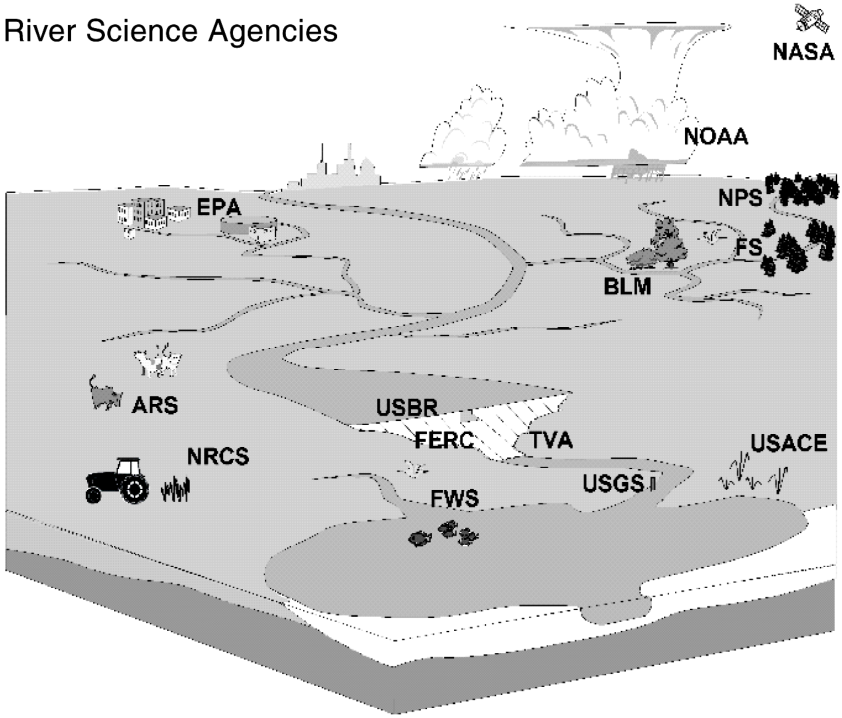


FIGURE 3-1 Federal agencies involved in river science.

and overseas (http://www.hec.usace.army.mil/). USACE field activities (divisions and districts) are responsible for the operations of dams, levees, and other water resource systems and structures throughout the nation. As part of this mission, USACE conducts, often in coordination with the USGS, monitoring of rivers that affect or are affected by these works. The USACE can then use this information to better understand and thus prevent the avulsion of river structure. In addition, USACE conducts project-specific adaptive management, mitigation, and restoration programs designed to improve the environmental sustainability of their projects. These efforts frequently parallel the scientific activities of the Biological Resources Discipline of USGS.

U.S. Bureau of Reclamation (Department of the Interior)—Responsible for development, operation, and management of water supply and related ecosystem management activities in the 17 western contiguous states. The bureau administers a science and technology program that researches, develops, demonstrates, and deploys "state-of-the-art technology to find new tools, better understand water systems, and develop flexibility in Bureau operations." Research and development projects include ones focused on both biology and water resources and include efforts such as investigating ecological interactions in small complex habitats for use in refugia design in regulated rivers, insuring fisheries have adequate amounts of water delivery through effective monitoring of fish movement, integrating state-of-the-art geophysical and groundwater-quality logging technologies for characterization of groundwater resources, and using remote sensing technology to facilitate detection of river system changes. The bureau also studies sediment transport associated with dam removal (http://www.usbr.gov/research/propc05/reviewer/public_main.cfm).

Fish and Wildlife Service (Department of the Interior)—Responsible for protection of migratory birds, endangered species, certain marine mammals, and freshwater and anadromous fish. A major function of the Fish and Wildlife Service (FWS) is the identification and recovery of threatened and endangered species under the Endangered Species Act. The FWS consults with other federal agencies and renders "biological opinions" on the effects of proposed federal projects on endangered species. The FWS lost most of its research capacity when most of its research scientists became part of the National Biological Survey, which was eventually transformed into the Biological Resources Discipline of the USGS. Their decentralized workforce concentrates mostly on resource management and regulation, but some focused research relating to management activities is still done. An example is in New Mexico, where refuge and ecological services programs support river (endangered species) research and riparian (endangered species as well as ecosystem-level) research and monitoring along the Rio Grande River.

Environmental Protection Agency—Establishes drinking-water-quality standards, regulates and funds wastewater management, and monitors wetlands, oceans, and watersheds. The Environmental Protection Agency (EPA) jointly administers (with USACE) the Clean Water Act's Section 404 Program. The EPA also monitors progress of national programs for total maximum daily load (TMDL) pollutants and for reducing nonpoint-source pollution. The EPA efforts in river science are led by its Office of Research and Development. The majority of this research is "in the life sciences (primarily biology and environmental biology)." Approximately 45 percent of its research and development is performed in EPA laboratories, nearly 33 percent in colleges and universities, and 16 percent by industrial firms (http://www.engineeringpolicy.org/EPA.html).

The EPA's Environmental Monitoring and Assessment Program (EMAP) is a long-term research effort to enable status and trend assessments of aquatic ecosystems across the United States with a known statistical confidence (USEPA, 2002b). EMAP's goal is to develop the scientific understanding for translating environmental monitoring data from multiple spatial and temporal scales into assessments of current ecological conditions and forecasts of future risks to our natural resources. EMAP has addressed the condition of estuaries, streams, and lakes in selected geographic regions. Data collected includes physical habitat, nutrients, and other commonly measured field parameters, and biological communities (algae, benthic invertebrates, and fish). The program interacts with many USGS offices, such as the Mid-Atlantic Integrated Assessment (MAIA) (www.epa.gov/maia/). EMAP uses a probabilistic sampling design to select sites with specific characteristics. This statistical approach is very different from that of the USGS's National Water-Quality Assessment Program (NAWQA), discussed later in this chapter. NAWQA deterministically selects both its study units to represent different hydrologic environments with different contaminant sources and its individual monitoring sites to determine representative water-quality conditions relative to important environmental settings in the study unit.

Many individual EPA research studies also monitor conditions in major rivers and collect samples of water, sediments, plants, insects, and fish for analysis (http://www.epa.gov/ord/).

Federal Agencies with Research Indirectly Supporting River Science

Agricultural Research Service (U.S. Department of Agriculture)—The USDA's primary in-house scientific research agency. The agency employs about 7000 people, including 2000 scientists who work at about 100 locations nationwide. Within its Natural Resources and Sustainable Agricultural Systems focus area much of the research applies to river science. These include areas of water quality and management, soil resource management, global change, rangeland, pasture and forages, and manure and byproduct utilization. Topics include work on hydrologic, chemical, and biological processes influencing the quality of water exiting agricultural lands, exploring the effectiveness of riparian buffers and vegetative filters so as to mitigate agricultural pollution, and enhancing soil erosion prediction technology to improve conservation planning and environmental protection (http://www.ars.usda.gov/research/programs.htm).

National Oceanic and Atmospheric Administration—Includes the National Ocean Service, the National Marine Fisheries Service, and the National Weather Service. The National Ocean Service works to preserve and enhance the nation's coastal resources and ecosystems along 95,000 miles of shoreline and 3.5 million square miles of coastal ocean. The National Marine Fisheries Service provides stewardship for living marine resources and endangered diadromous fishes through science-based conservation and management, as well as the management, conservation, and protection of living marine resources within the United States' Exclusive Economic Zone. The National Weather Service provides the United States, its territories, adjacent waters and ocean areas with weather, hydrologic, and climate forecasts and warnings, including flood warnings, which are of particular interest to river science. These services assist in the protection of life and property and enhance the national economy. The National Oceanic and Atmospheric Administration (NOAA) also provides data and products to form a national information database and infrastructure, which can be used by other governmental agencies, the private sector, the public, and the global community. The Office of Oceanic and Atmospheric Research (OAR) studies ocean and coastal resources, weather, air quality, and climate. NOAA's research focuses on "enhancing the understanding of environmental phenomena such as tornadoes, hurricanes, climate variability, solar flares, changes in the ozone, El Niño/La Niña events, fisheries productivity, ocean currents, deep sea thermal vents, and coastal ecosystem health" (http://www.noaa.gov/research.html).

National Aeronautics and Space Administration—Investigates and funds external research concerning water budgets, land use and land-use change, and water quality of large river systems, much of this through its Terrestrial Hydrology Program. Data from the Advanced Microwave Scanning Radiometer–EOS (AMSR-E) instrument is providing 25-km-resolution soil moisture and snow water equivalent products that can be used in conjunction with streamgaging data for hydrologic modeling. Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat imagery have been used to show snowcover and river-floodplain interactions and to estimate suspended sediment loads and/or chlorophylla in large rivers.

Federal Agencies with Management Responsibilities Affecting River Science

Natural Resources Conservation Service (U.S. Department of Agriculture) (formerly the Soil Conservation Service)—Promotes land-use management practices aimed at reducing erosion and promoting conservation. The Natural Resources Conservation Service (NRCS) also acts to reduce the risks of floods and droughts in the nation's watersheds. Through the National Water and Climate Center (NWCC), NRCS seeks to "lead the development and transfer of water and climate information and technology which support natural resource conservation" (http://www.wcc.nrcs.usda.gov). The NWCC conducts water-related project activities in five key areas: interagency coordination, special projects, technology transfer, water policy, and watershed marketing (http://wmc.ar.nrcs.usda.gov/about/).

Bureau of Land Management (Department of the Interior)—Responsible for managing hundreds of millions of acres of grasslands, forests, high mountains, arctic tundra, and deserts, mostly in the western United States. The resources and uses it oversees include energy and minerals, timber, forage, wild horse and burro populations, fish and wildlife habitat, and wilderness areas. The Bureau of Land Management (BLM) is also responsible for portions of 38 wild and scenic rivers, which have a combined length of over 2000 miles (http://www.blm.gov/nhp/facts/index.htm). The BLM's Research and Development Program focuses on *relevant* uses of new data, information, and knowledge to improve the management of the nation's lands and resources, including rivers. Although the BLM does its own research, it relies heavily on the USGS, which acts as the primary research-science support organization for the entire Department of the Interior (http://www.blm.gov/budget/ 2007just/2007researchanddevelop.pdf).

National Park Service (Department of the Interior)—Responsible for preserving, protecting, and sharing the land and cultural legacies of nearly 400 distinct areas that cover more then 84 million acres. In managing the water resources on these lands, including sections of designated Wild and Scenic Rivers, the National Park Service (NPS) works in partnership with multiple government agencies and cooperators to share information and undertake special projects. One example of the NPS efforts to improve water resource management is the Hydrology and Watershed Management Program, which administers programs in the areas of watershed condition assessment, surface-water hydrology, floodplain management and compliance, groundwater use and protection, and stream and riparian management (http://www.nature.nps.gov/water/hydrology.cfm).

Tennessee Valley Authority—Established by Congress in 1933 primarily to provide navigation, flood control, and agricultural and industrial development and to promote the use of electric power in the Tennessee Valley. It is the nation's largest public power provider, and its 2004 strategic plan is focused primarily on changes in its business environment (i.e., energy markets and financing) (http://www.tva.gov/abouttva/stratplan/tva_strategic_plan.pdf). Tennessee Valley Authority (TVA) river management emphasizes flood reduction, river transportation, power production, water quality, recreation, and wise land use. The TVA conducts extensive monitoring of its reservoirs and streams for environmental health (http://www.tva.gov/environment/-ecohealth/index.htm), but its research in river science areas is limited. At its research facility in Muscle Shoals, Alabama, TVA develops tools and methods to minimize and clean up pollution from industrial, municipal, and agricultural systems. The major focuses are atmospheric sciences, biotechnology, contaminated site remediation, and prevention of water pollution from nonpoint sources. The Muscle Shoals reservation houses the nation's leading constructed wetlands R&D facility (http://www.tva.gov/abouttva/keyfacts.htm#protectenv).

Federal Energy Regulatory Commission—An independent agency responsible for reviewing, licensing, relicensing, and decommissioning federally licensed hydroelectric power dams. The Federal Energy Regulatory Commission (FERC) has no specific river science activities although the scientific effort that is undertaken as part of periodic licensing contributes considerable information about the aquatic ecosystem.

STATE AGENCIES AND TRIBAL GOVERNMENTS

Under the U.S. Constitution, state governments exercise title and rights to property, including the use of water within their states. Native American tribes exercise responsibility as custodians of the public trust for protection of waters and for management of water resource activities on tribal lands. Most states and many tribes have established agencies, which parallel many federal agencies, to deal with water-related issues. The federal government, however, has ultimate authority over the United States' navigable waters for the regulation of activity and use of water for the production of hydroelectric power and to prevent pollution in all waters. States set water-quality standards for rivers within their jurisdiction and submit these standards for approval by the EPA. In turn, they conduct water-quality monitoring and make periodic assessments that are also submitted to the EPA. They also monitor flow parameters either on their own or as cost-share partners with the USGS. In many cases they also gather and store data concerning aquatic flora and fauna within their boundaries, conduct studies to assist in management of riverine areas, and work on specific programs and projects in conjunction with other federal agencies, such as the Fish and Wildlife Service.

The International Association of Fish and Wildlife Agencies (IAFWA) represent the government agencies—mostly at the state level—responsible for North America's fish and wildlife resources. IAFWA has the lead role in the National Fish Habitat Initiative, a broad-based effort targeted at fisheries restoration in key watersheds. While the U.S. Fish and Wildlife Service and National Marine Fisheries Service are the principal federal partners, the Biological Resources Discipline of the USGS also supports the initiative.

The Instream Flow Council (IFC) was formed in 1998 by state and provincial fish and wildlife management agencies in the United States and Canada. Its primary mission is "to improve the effectiveness of state and provincial instream flow programs and administrators in protecting, maintaining and restoring aquatic ecosystems" (http://www.instreamflowcouncil.org). Over the next 20 years, the IFC hopes to become a recognized authority and source of information about instream flow science, policy, and administration. They have published several editions of the book "Instream Flows for Riverine Resource Stewardship (Annear et al., 2002).

River basin commissions are another kind of multistate entity with an interest in rivers. For example, the newly formed Missouri River Association of States and Tribes (MoRAST) represents nonfederal game and fish agencies, tribal interests, and water management agencies from seven states and a tribal water rights coalition. Previously, the state water management agencies and the tribal coalition belonged to the Missouri River Basin Association, while the state game and fish agencies belonged to the Missouri River Natural Resources Committee. The Delaware River Basin Commission (DRBC), whose members include representatives from the basin states of Delaware, New Jersey, Pennsylvania, and New York, and a federal representative, is another such organization. This regional body has the force of law to oversee a unified approach to managing the river system without regard to political boundaries (http://www.state.nj.us/drbc/). The upper Colorado, Ohio, and Susquehanna Rivers also have river basin commissions.

River basin commissions are often more focused on policy than science. However, they often have interests in applied science (e.g., flow management, water supply, flood warning and loss reduction, water quality, and effects of river basin management on the downstream estuary [Robert Tudor, DRBC, written communication, June 14, 2005]).

NONGOVERNMENTAL ENTITIES

A wide variety of nongovernmental entities are involved in aspects of river science. Generally, their river science activities are supported by agencies of the government at both state and local levels. These entities include academic institutions, private firms, and natural resources advocacy groups.

Academic institutions conduct considerable river science research and in some cases collect data to support this research and develop models or techniques that are used for analysis or decision support. Both their data and tools are frequently made available to federal and state agencies. The National Science Foundation (NSF) supports both individual and group-related river science research. Single investigator and small team research grants often provide an innovative source for new theory development. These compliment the NSF's support of several academic consortia or networks in water or water-related fields. These include the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI), the National Ecological Observatory Network (NEON), and the Collaborative, Large-scale, Engineering Analysis Network for Environmental Research (CLEANER). These initiatives are still in an early phase of development, but when they develop they will likely be major drivers in river basin research and potential partners for the USGS. All of these initiatives emphasize observatories in which geographically distributed network sensors and other instrumentation and infrastructure will be used to answer questions related to water quality, the water cycle, ecology, and related topics.

An existing but more loosely connected network is the Long Term Ecological Research (LTER) Network, also supported by the NSF. This is a collaborative effort of more than 1800 scientists and students investigating ecological processes in 26 sites that represent many different ecosystems and research emphases. Many of these sites include rivers in their study area and are both producers and consumers of river data and information.

The National River Restoration Science Synthesis (NRRSS) Project is a national-level synthesis of stream restoration projects that involves researchers from many different academic institutions. Its goal is to "analyze the extent, nature, scientific basis and success of stream river restoration projects, and to present this information in a way that is useful to scientists, restoration practitioners, and those making policy decisions on what kinds of projects ought to receive priority for funding and implementation" (http://www.restoringrivers.org). The program has a database of over 37,000 restoration sites. While the USGS is involved primarily in large-scale river restoration activities, the synthesis of data from this extensive database is likely to provide input for river science activities at the USGS in coming years.

Significant work in river science is also accomplished by private firms engaged in engineering and environmental and natural resources consulting, including many international firms with worldwide experience. These firms conduct hydrographic surveying, water parameter monitoring, and model development for governments and other organizations. They also are active in developing specialized equipment to support their activities. While their software is normally commercially available, the products of their data collection and analysis typically become the property of their clients who may or may not share the results outside of their organizations. With the advent of increased government pressure to contract for commercially available services, many of these firms (as well as academic institutions) compete with federal and state agencies to conduct river-science-related data gathering, modeling, and analysis.

Many natural resources advocacy groups have well-defined river science programs, although usually they rely on federal and state resources for basic data. Their role in river science is generally limited to analysis of data, development of strategies that result from this analysis and in some cases, support of carefully designed riverine restoration or enhancement experiments. Many are also active in their support of federal river science data collection programs and frequently testify on behalf of these programs.

American Rivers, Trout Unlimited, and The Nature Conservancy are three examples of nonprofit organizations actively involved in river science. American Rivers is an organization dedicated to protecting and restoring rivers and the life they sustain. They work on a variety of issues, such as river restoration, instream flows, adaptive management, ecosystem services, dam removal, and salmon habitat. They depend heavily on the USGS for flow and water-quality data, along with independent, technical assistance (A. Fahlund, American Rivers, written communication, June 14, 2005). Trout Unlimited—an organization with a mission to conserve, protect, and restore North America's trout and salmon fisheries and their watersheds—participates in an ever increasing number of watershed, conservation, and river restoration projects. They have numerous research partnerships with federal agencies focused on restoring watersheds to "benefit trout, salmon, rivers, and the communities that enjoy them" (http://www.tu.org). The Nature Conservancy is an organization focused on protecting land and water habitats to preserve plants, animals, and natural communities. Their Sustainable Waters Program targets protection of freshwater ecosystems by advancing policies and conservation approaches that promote ecologically sustainable water management. In this effort they focus on research in flow modeling and habitat assessment to better understand the water needs for river ecosystems. Virtually all such research efforts rely heavily on USGS river flow information as a foundation and are further supported by USGS biological and land-use and land-cover information.

It is important to note that nongovernmental organizations conduct activities in locations and at times that are of most interest to them and their clients or supporters, whereas government organizations must operate on a continuous and national basis.

USGS PROGRAMS

Within each of the disciplines at the USGS, there are programs designed around specific tasks as well as broader programs of general data collection monitoring and analysis. Many existing programs deal with rivers and river science issues, and would naturally contribute to an integrative river science initiative within the USGS (http://www.usgs.gov/science/). The following sections contain a sampling of these programs within the USGS.

Biological Resources Discipline

Fisheries: Aquatic and Endangered Resources Program

With a mission of providing scientific research and support to the Department of the Interior, other federal agencies, the states, tribes, and the nation's natural resource managers, this program is focused on the study of fish, fisheries, aquatic invertebrates, and aquatic habitats. The program includes (1) systematic research to evaluate factors that affect aquatic organism health, population fitness, biological diversity, and aquatic community and habitat function, with a special focus on imperiled and at-risk species and habitats; (2) investigations to determine the physiological, behavioral, and genetic responses of aquatic populations to environmental change; (3) studies of advanced techniques in microbiology and genetics for diagnosing and controlling disease in fish and other aquatic organisms; and (4) development of predictive models of population and community interactions to assist in forecasting species abundance and describing predator-prey and habitat relationships. The program seeks to better understand aquatic organism health, aquatic species at risk, aquatic species and habitats, restoration science, and diversity, species interactions, and life history strategies (http://biology.usgs.gov/farp/index.htm).

Invasive Species Program

When certain species are introduced into an ecosystem, they can have negative impacts on the environment, the economy, and human health. The Invasive Species Program conducts research on all aspects dealing with terrestrial and aquatic invasive species. This research includes preventing the introduction of non-native species to an ecosystem through early detection and rapid response to eradicate invasive species, and in locations where invasive species are already established the program works to develop methods for controlling the invasion and promoting ecosystem restoration (http://biology.usgs.gov/invasive/). The USGS's Biological Resources Discipline Science Center, in Fort Collins, Colorado, houses the National Institute for Invasive Species Science, a consortium of government and nongovernment organizations involved in research on effective responses to invasive species. Their science information efforts also contribute to the National Biological Information Infrastructure Invasive Species Information Node (http://invasivespecies.nbii.gov).

Status and Trends of Biological Resources Program

To aid in the protection and restoration of living natural resources, this program provides science information on the abundance, distribution, productivity, and health of biological resources, and tracks their changes over time. Some of the goals of the program include (1) developing a National Monitoring Framework that integrates biological resources information from multiple sources and spans a range of spatial and temporal scales, (2) developing protocols and methods for designing experiments, monitoring, and analyzing results to measure the status and trends of biological resources, (3) collecting and archiving data in cooperation with partners, and (4) synthesizing information on the status and trends to meet the needs of the scientific community, land and resource managers, policy makers, and the public. The program involves long-term monitoring to detect degradation, identifying emerging problems, assessing the effectiveness of management solutions, and validating predictive models. The seminal publication *Status and Trends of the Nation's Biological Resources* (USGS, 1998), which represented the first comprehensive summary on this topic, is an example of their synthesis efforts (http://biology.usgs.gov/status_trends/).

Terrestrial, Freshwater, and Marine Ecosystems Program

This program conducts research to better understand the factors that control the structure, function, and conditions of terrestrial, freshwater, and marine ecosystems. These ecosystems provide many goods and services, from mitigating the impacts of floods and droughts to purifying air and water. The program provides science information to help manage and restore these ecosystems. The Upper Midwest Environmental Science Center (UMESC) is an example of how the program investigates the nutrient dynamics in large rivers, the role of hydrologic regimes on nitrogen cycling and biota, and management strategies for reducing nutrient fluxes to coastal areas. As part of this effort, models were developed to predict the distribution and abundance of fish, invertebrates, and vegetation on the upper Mississippi River based on river water quality and habitat conditions (http://biology.usgs.gov/ecosystems/).

Biological Resources Science Centers

Much of the science performed within the Biological Resources Discipline of the USGS takes place at the biological resource science centers. A lot of the work falls under programs that have been mentioned above, but these centers are worth mentioning in their own right. For example, UMESC, which was noted above under the Terrestrial, Freshwater, and Marine Ecosystems Program, runs a variety of biological and interdisciplinary river science projects in the Ohio and Mississippi River basins. These include extensive work on restoration of degraded habitats, nutrient enrichment, amphibian and mussel research and monitoring, control and management options and ecological consequences of invasive species, and decision support model development to bring biologists and engineers together to better plan habitat projects and to aid in conflict resolution over navigation development and endangered species (http://www.umesc.usgs.gov).

UMESC also runs a Long Term Resource Monitoring Program (LTRMP) to understand physical and ecological trends in the Upper Mississippi River System, in support of management activities of the USACE. The program investigates the interactions among river navigation activities, sedimentation, water level fluctuations, aquatic vegetation, and fisheries populations. LTRMP combines information on the river and its watershed, such as channel bathymetry, land use and land cover, and Geographic Information Systems (GIS) data, with monitoring of the river's vegetation, water quality, fisheries, and macroinvertebrates. Monitoring is based on a component sampling model, which uses a probabilistic sampling design. Monitoring takes place at six 25-to-50-mile river reaches within both impounded and unimpounded sections of the Mississippi and Illinois Rivers, and samples across the geomorphic gradients. For data management LTRMP uses an open access paradigm to provide query tools for quality-assured ecological datasets, and graphical browsers for scientific exploration of databases. LTRMP also uses monitoring data to provide science-based information on resource management issues, producing decision support and synthesis reports in collaboration with the USACE.

The Columbia Environmental Research Center's River Studies Branch also carries out basic and applied research in support of ecosystem-level management of large rivers, streams, and floodplain wetlands, with their strongest programs focused on the Missouri River basin (including the Yellowstone and Platte Rivers). Their topics include ecology and life history of aquatic macroinvertebrates and sturgeon, linking reservoir management, channel engineering, and land-use change to habitat quality and self-sustaining ecosystem dynamics, development of decision support systems for ecology and restoration of streams, competition for habitat between native and invasive species, and impacts of water-quality changes (e.g., urban runoff and sewage effluent) on various amphibian and macroinvertebrate species.

The Fort Collins Science Center, which was referred to earlier in the section on the "Invasive Species Program," seeks to "provide managers with credible science-based information on the interrelationships among the physical, chemical, aquatic, and biological components of natural systems, especially river basins, for resource management decision making" (http://www.fort.usgs.gov). Their science topics include models and applications for resource management issues, habitat and biological linkages in river corridor environments, water-quality improvement, economic measures for natural resource benefits, altered flow regime effects on native fish populations, sediment transport studies, and landscape-scale changes in river basins.

Many of the USGS biological resource science centers are also active in the Priority Ecosystems Science Initiative, described below under "Crosscutting Programs." These include the Florida Integrated Science Center (Everglades), Patuxent Wildlife Research Center (Chesapeake Bay), and the Western Ecological Research Center (San Francisco Bay).

Geography Discipline and National Geospatial Program Office

Geographic Analysis and Monitoring

The Geographic Analysis and Monitoring (GAM) Program provides scientific assessments on land surface changes and the impacts of these changes on ecosystem health, climate variability, biogeochemical cycles, hydrology, and human health. The program investigates trends through long-term studies of the land-use and disturbance histories, provides high-resolution land-use and land-cover maps, and carries out geographic studies to understand the reasons for land surface changes. The program also supports case study applications on related environmental, natural resource, and economic issues (http://gam.usgs.gov). The River Observatories for Management Applications Project in the Susquehanna River watershed is one example; the project seeks to understand how changes in land use/land cover and urbanization have contributed to sediment mobilization and sediment influxes into the Chesapeake Bay (http://erg.usgs.gov/rit/).

Land Remote Sensing Program

The fundamental goal of the Land Remote Sensing (LRS) Program is to provide the federal government and the public with a primary source of remotely sensed data and applications. Its objectives are to acquire regional and global remotely sensed datasets from multiple sources, participate in defining and developing future satellite missions, ensure the preservation of and access to the nation's remotely sensed land data, and expand the understanding and applications of remotely sensed data (http://remotesensing.usgs.gov). The program includes a project to use remotely sensed datasets for discriminating and mapping land surface imperviousness, which relate to flooding and water quality of rivers.

Much LRS and GAM work is carried out by the USGS Center for Earth

Resources Observation Systems (EROS) in Sioux Falls, South Dakota. EROS is involved in products such as the National Elevation Dataset, and derivative products such as the Elevation Derivatives for National Applications (EDNA) database. EDNA provides 30-meter-resolution data layers, including aspect, contours, filled digital elevation models, flow direction, slope, and synthetic streamlines. These can be used in flood analysis investigations, pollution studies, and hydroelectric projects (http://edna.usgs.gov). The Land Cover Institute is also housed at EROS.

The National Map

In the 1990s, the USGS completed a national mapping effort, which began in the late 1800s, to establish a comprehensive coverage of the nation's topography. The next generation of mapping services at the USGS will be provided by The National Map, an online geospatial information resource that provides a seamless, continuously maintained, nationally consistent set of base geographic data. The National Map distributes both maps and data of topography, orthorectified aerial and satellite imagery, the location of rivers, roads, railways, and political boundaries, as well as land cover information. In the future the system will seamlessly integrate online datasets for multiple sources. The USGS efforts on The National Map not only guarantee the completeness, consistency, and accuracy of the archival data but also provide coordination on data gathering through its partnerships with federal, state, and local government agencies and with the private sector.

The National Map has recently been brought into the newly created National Geospatial Program Office. This realignment brings it into closer contact with two other national, cross-agency initiatives to implement the National Spatial Data Infrastructure (NSDI): 1) the Federal Geographic Data Committee, which provides coordination, standards and policy, and training on geospatial data for The National Map, and (2) the Geospatial One-Stop, which is a portal for accessing The National Map, and provides a common infrastructure for data discovery, access, and harvesting (http://nationalmap.gov).

Geology Discipline

Earth Surface Dynamics

The Earth Surface Dynamics (ESD) Program focuses on researching the interactions between climate, earth surface processes, landscape, and ecosystems at timescales from years to millennia. The ESD program provides a long-term perspective on topics related to river science, through studies such as the Holocene alluvial stratigraphy and chronology of the eastern United States and the paleohydrology of the intermountain west. As part of the USGS Global Change

Research effort, the ESD program integrates work across the USGS disciplines on topics ranging from the carbon cycle and hydroclimatology to the interactions of climate with physical, biogeochemical, hydrologic, and human systems (http://geochange.er.usgs.gov).

Coastal and Marine Geology Program

The Coastal and Marine Geology Program studies the resources of coastal and marine environments, the natural and human induced changes in these environments, and the impacts of geological hazards such as hurricanes, earthquakes, landslides, and tsunamis. Their research efforts also include studies of sediment and nutrient fluxes to estuaries for priority ecosystems, including the San Francisco Bay, the Chesapeake Bay, and South Florida. Their series of coastal classification maps describes local geomorphic features as a step toward determining the hazard vulnerability of various areas. These maps integrate information on beach width, dune elevations, overwash potential, development density, prior storm impacts, and beach stability (http://marine.usgs.gov).

Water Resources Discipline

National Streamflow Information Program

The USGS streamgaging network underpins many of the research and monitoring activities encompassed within our definition of river science. The first USGS streamgaging station was established on the Rio Grande near Embudo, New Mexico, in 1889. Now, the USGS operates about 7400 gaging stations in the United States and its territories; the vast majority of these stations are now equipped with satellite telemetry systems that provide real-time data for many purposes, including water-resources planning and flood forecasting. The USGS also maintains records for approximately 11,500 discontinued stations.

Concerns about the health of the existing USGS streamgaging network and its ability to meet the growing needs for streamflow information led to the formation of the National Streamflow Information Program (NSIP). The NSIP plan has five elements:

1. a stable, modernized streamgaging network that addresses core federal and cooperator needs;
2. collection of critical information during floods and droughts;
3. periodic assessments and evaluation of streamflow characteristics to assess the impacts of climate and land-use change;
4. development of a highly reliable system for delivering data to users; and
5. research and development to build better data collection, delivery, and interpretation capabilities for the future.

In 2004, a National Research Council committee strongly endorsed the general design and goals of NSIP. To assure the long-term viability of the USGS to satisfy *national needs* for streamflow information, the report included the recommendation for direct federal support for a base streamgaging network (NRC, 2004d). It also recommended that:

- The ultimate goal of NSIP should be the ability to generate *streamflow information* with quantitative confidence limits at any location—not just gauged locations—in the stream network; and
- The principle of adaptive management should be incorporated explicitly into the NSIP, including periodic reevaluation of the national gage network to ensure it continues to meet the nation's current and *anticipated future needs* for streamflow information.

Of greatest relevance to this report, the NRC report highlighted the vital role of NSIP in supporting a national river science initiative. The report identified the needs and opportunities for characterizing river systems using a more comprehensive data delivery system that focused on streambed characteristics and sediment and velocity distributions in addition to discharge. The report also identified crest stage data, slope-area data from flood studies, gaging station channel geometry, and bed sediment characteristics as historical data of value for river science if "rescued" from historical, nondigital files. Beyond the data values and measurements, the committee recommended that the USGS identify watersheds that have high-quality hydrologic and land-use/land-cover information as candidate basins in which to emphasize data recovery and synthesis. Such a "discovered" network was proposed as a pragmatically identifiable set of experimental watersheds to be used to support river science investigations of how land-use change affects river systems. The watersheds defined by the "sentinel" NSIP river gages (gages identified to provide monitoring of long-term trends in the nation's streamflow) were similarly suggested to be candidate watersheds for expanding the characterization of stream morphology reference points, in addition to their NSIP role as streamflow reference points.

Examples that highlight the value of information generated from the national streamgaging network include regional and national applications in climate change (Figure 3-2), flooding (Figure 3-3), and ecohydrologic classifications (Poff, 1996).

National Stream Quality Accounting Network

Two national monitoring programs routinely monitor river water quality: the National Stream Quality Accounting Network (NASQAN) and the National Water-Quality Assessment (NAWQA) Program. NASQAN is federally funded (Fiscal Year 2005 about $2.3 million) and has been in operation since 1973.

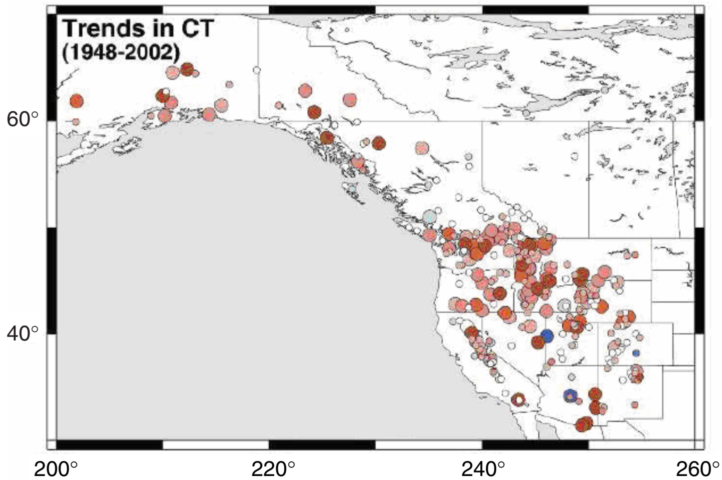


FIGURE 3-2 Trends in the date of center of mass of annual flow (CT) for snowmelt-dominated gauges. Shading indicates magnitude of the trend expressed as the change (days) in timing over 1948-2000. Larger symbols indicate statistically significant trends at the 90 percent confidence level. The figure shows that widespread and regionally coherent trends toward earlier onsets of springtime snowmelt and streamflow have taken place across most of western North America due to higher winter and spring temperatures. SOURCE: Adapted, with permission, from Stewart et al. (2005). © 2005 by the America Meteorological Society.

NASQAN was created to address difficulties identified by Wolman (1971) in performing statistical analysis of water quality, namely, short record length and changes in locations and sampling frequency. The original NASQAN objectives included (1) account for the quantity and quality of water moving within and from the United States, (2) depict areal variability, (3) detect changes in stream quality, and (4) lay the groundwork for future assessments of change in stream quality (Ficke and Hawkinson, 1975).

NASQAN stations are located at the terminus of hydrologic accounting units, which are identified with the third-order hydrologic basin classifications developed by the USGS Office of Water Data Coordination (Langford and Davis, 1970). Sample analysis includes nutrients along with major ions, trace elements, field parameters, and indicator bacteria. At the peak of operation, NASQAN's network included more than 500 stations that were sampled monthly.

Over the years, NASQAN operations have been reduced or changed due primarily to budget constraints. By 1990, about 400 stations were sampling only on a quarterly scheme. In 1996, NASQAN underwent a major redesign that reduced the number of stations to 40 but increased the sampling frequency to

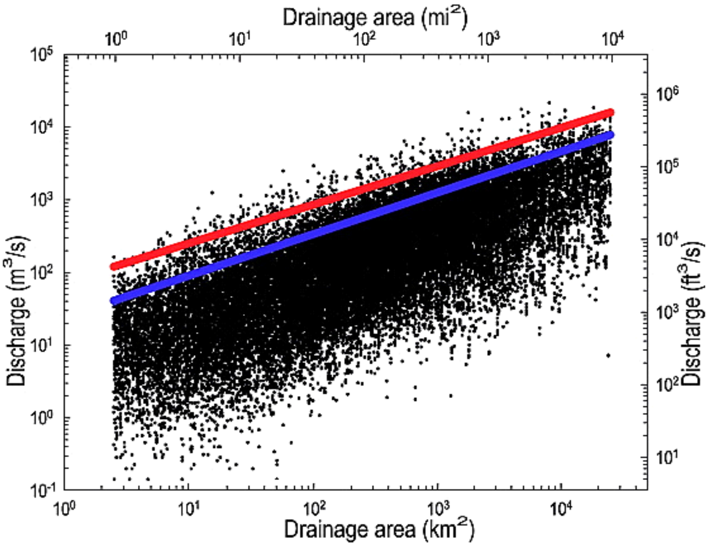


FIGURE 3-3 Top 10 percent of annual peak discharges from each of 14,815 streamgaging stations. These data were further stratified on a unit discharge basis into ~ 90th and ~ 99th percentiles by the depicted lines. Within the conterminous United States, the greatest concentration of exceptional unit discharges is in central Texas, where maximum rainfall amounts apparently coincide with appropriate basin physiography. This may help explain why Texas has nearly twice the average annual flood-related fatalities of any other state. SOURCE: Adapted, with permission from O'Connor and Costa (2004). © 2004 by American Geophysical Union.

once a month. They also added three high-flow samples per year, and the constituent coverage was expanded to include pesticides and suspended sediment chemistry. In Fiscal Year 2005, NASQAN operated 33 stations, which included stations on the Mississippi (17 sites), Rio Grande (8 sites), Yukon (4 sites), Colorado (2 sites), and Columbia (1 site) Rivers.

Nutrient data has been included in every NASQAN sample collected since 1973. As a result, many stations have 20 years or more of nutrient measurements. One of the most productive uses of this dataset has been in a national model of total nitrogen and total phosphorus transport, using the SPARROW (Spatially Referenced Regression on Watershed attributes) model (Smith et al., 1997). They used a subset of 414 stations from NASQAN to estimate total nitrogen yield from watersheds in the conterminous United States. Such modeling has also been valuable in estimating the transport of total nitrogen from subbasins of the Mississippi River to the Gulf of Mexico, which has helped in investigating questions and concerns about hypoxia in the Gulf of Mexico.

The historical and current NASQAN data are stored in the USGS National Water Information System and are available to the public after quality assurance. With the major network changes in 1996, the USGS created a CD-ROM of all the historical (1973-1995) NASQAN data (http://water.usgs.gov/pubs/dds/wqn96cd/-html/report/contents.htm). This data publication outlines the history of the network operations, including the smaller Hydrologic Benchmark Network. Recent NASQAN data is available at http://water.usgs.gov/nasqan/data/index.html. A summary of the data collected by the redesigned network operations is at http://water.usgs.gov/nasqan/-progdocs/wri014255/index.htm, and a collection of articles written after the first five years of operating the redesigned NASQAN is available at http://www3.interscience.wiley.com/cgi-bin/jissue/82002952.

National Water-Quality Assessment Program

The second national river water-quality monitoring program, the NAWQA Program, began in 1991. NAWQA goals include (1) a description of water-quality conditions, (2) identification of time trends in water-quality conditions, and (3) an understanding of the causes, both natural and anthropogenic, for the conditions and time trends. NAWQA has created more than 1000 publications and a unique nationally consistent water-quality dataset. Much of the NAWQA information is available at http://water.usgs.gov/nawqa/. NAWQA has conducted studies in 51 major river basins and aquifer systems, which cover about one-half the land area of the conterminous United States.

Studies by the NAWQA Program from 1991 to 2001 describe water-quality conditions in nearly 120 agricultural and 35 urban watersheds. The findings show that for urban and agricultural areas, nonpoint chemical contamination by nutrients is an issue. The findings also show that water-quality conditions and aquatic health vary according to a complex combination of land and chemical use, land-management practices, human population density, and watershed development, as well as with season and natural features, such as soils, geology, hydrology, and climate.

In the second decade of the NAWQA Program (2001-2010), in-depth and process-oriented studies are underway to investigate the effects of nutrient enrichment on aquatic ecosystems, as well as the sources, transport, and fate of nutrients and other agricultural chemicals in streams and shallow groundwater. The NAWQA Data Warehouse (http://water.usgs.gov/nawqa/data) is a publicly available database containing results from samples collected at about 6400 stream sites, 7000 wells (including more than 2000 domestic wells), and more than 1000 sites where fish, invertebrate, and algal communities (species and relative abundance) data are collected. These samples have been analyzed for nutrients, pesticides, and a variety of other contaminants. Data can be retrieved by select-ing options such as concentrations for an individual or group of chemicals or data from one or multiple states, counties, or river basins.

Toxic Substances Hydrology Program

The Toxic Substances Hydrology Program provides scientific information on the contamination of surface water and groundwater, land, and atmosphere by toxic substances, such as organic chemicals, pathogens, and excessive nutrients. This information is then used to aid in developing policy and remediation measures to protect human and environmental health. Components of the program include field investigations and process-based studies of contamination affecting aquatic ecosystems. The development of predictive models to assess the fate and transport of contaminants in the environment is also an integral part of their effort (http://toxics.usgs.gov).

National Research Program in the Hydrological Sciences

The National Research Program (NRP) is a centrally coordinated program that conducts basic and problem-oriented research within the Water Resources Discipline. The program focuses on (1) the study and application of hydrologic principles to particular geographic settings or water-resources problems, and (2) fundamental research addressing hydrologic processes and principles that are related to broad geographic areas or problems (USGS, 2005). The program, initiated in the late 1950s, has grown to span components integral to river science. Recent activities include experiments to entrain sediments and rebuild lost sandbar deposits along the river channel during controlled flood releases from Glen Canyon Dam, the use of environmental tracers to track nitrogen contamination, and investigations of biological and microbiological processes affecting water quality, ecology, and biogeochemistry of surface and groundwater (USGS, 2005). Scientists in the NRP are primarily located at the USGS Regional Centers in Reston, Virginia, Denver, Colorado, and Menlo Park, California, and provide scientific leadership on many areas within the Water Resources Discipline; many of the USGS's major initiatives on national water resources issues come from research initiated within the NRP. NRP scientists also support project teams within the WRD Water Science Centers and actively engage in other major programs of the USGS, including NSIP, NAWQA, and the Toxic Substances Hydrology program (http://water.usgs.gov/nrp/).

Cooperative Water Program

The Cooperative Water Program (Coop Program) was initiated in 1895 and continues to provide cost sharing for the USGS to partner with nonfederal water resources agencies (e.g., state, local, and tribal agencies, as well as conservation, water-supply, and flood-control districts). The three components of the program are data collection, interpretive studies, and national synthesis. In 2003, cooperators supported streamgaging at about 4200 stations, more than half of the entire streamgaging network (Taggart, 2004). Cooperators also supported monitoring of groundwater levels and, increasingly, water-quality monitoring for compliance with the total maximum daily load (TMDL) provision of the Clean Water Act. Data collected through these activities are publicly available through National Water Information System.

The USGS and its cooperators jointly plan their scientific work strategy to meet the local needs of the cooperator and also provides science information for the nation. For example, the Coop Program supports over 700 interpretive studies per year, often on emerging issues of national significance, such as the relationship between land-use changes and the physical habitat of streams (Jacobson et al., 2001). Because the data collection activities use nationally consistent procedures and quality assurance protocols, they provide critical information for national syntheses, including recent studies of both regional droughts and trends in streamflow and the development of predictive tools for estimating travel time in rivers. Current topics of national interest for the Coop Program include fluvial sediment, changes in flood frequency, a synthesis of water-quality information, and the determination of water needs for ecological functions (http://water.usgs.gov/coop/).

USGS Nutrient Projects

Besides the national monitoring programs, the Water Resources Discipline has many activities/projects that encompass assessment and research around nutrient issues, going beyond the routine monitoring of stream and groundwater conditions. These are done as special projects across USGS regional offices as well as individual research efforts. Past and current projects include nutrient budgets, nutrient sources and transformation, nutrient impacts on receiving waters and aquatic communities, and new/improved methods to measure nutrients.

An improved understanding of a system's nutrient budget is often an objective for various cooperative projects with state, county, or municipal agencies so as to better manage identified problems. Often the problems are excessive algae or other aquatic plant growth, which could result in aesthetic, taste, and odor issues.

Nutrient sources are of increasing interest because of TMDL requirements under the Clean Water Act and because nutrient source information can help identify where management should focus resources to improve or protect water quality. The USGS has used various techniques to identify nutrient sources. These include measuring nutrients from various land-use settings, including atmospheric deposition; using stable isotopes of nitrogen species, which often vary according to source; employing GIS databases on fertilizer use, manure applications, and animal feeding operations; and making use of models for nutrient movement and transformation, such as the previously mentioned SPARROW model. USGS interest in nutrient transformation includes looking at flow paths in streams, soil-unsaturated zones, streams, and aquifers to determine changes in nutrient species and mass balance.

USGS is also doing research on nutrient impacts to aquatic ecosystems. Ongoing studies include NAWQA through Topical Studies. Two of direct relevance to nutrient issues are Nutrient Enrichment on Ecological Systems (http://pubs.water.usgs.gov/fs11803/) and the Agricultural Chemical Transport Studies (http://pubs.water.usgs.gov/fs20043098/). An overview of NAWQA work on nutrient enrichment and criteria is at http://water.usgs.gov/nawqa/informing/nutrient.html.

Finally, the USGS is also studying ways of improving measurements of nutrient concentrations in the laboratory and in situ. For example, the Kjeldahl method in the laboratory has been replaced with a persulfate method, and field auto analyzers that will allow the continuous measurement of nutrient concentrations are being evaluated.

Crosscutting Programs

There are various interdisciplinary efforts at the USGS. These include formal programs, such as the Science Impact Program, housed in the office of the associate director for geography, whose goal is to increase the use and value of USGS science in decision making. They also include initiatives, such as the Priority Ecosystems Science Initiative, housed in the office of the associate director for biology, and the Amphibian Research and Monitoring Initiative, coordinated in the BRD and with "points of contact" in the water resources and geographic disciplines (as well as at the National Park Service, U.S. Fish and Wildlife Service, and Bureau of Land Management). In addition, there are less formal entities, such as the Human Health Coordinating Committee, which includes managers from such diverse units as the Toxic Substances Hydrology Program, National Wildlife Health Center, Mineral Resources Program, Geographic Analysis and Mapping Program, Cooperative Water Program, and Wildlife and Terrestrial Resources Program. Likewise, USGS Global Change Research activities are loosely coordinated through the Earth Surface Dynamics program of the Geology Discipline. The Priority Ecosystems Science Initiative is described in more detail below.

Priority Ecosystems Science Initiative

The Priority Ecosystems Science (PES) Initiative supports adaptive management of ecosystems through studies designed both to address local management needs for science information and to provide knowledge and approaches that can be transferred to similar ecosystems elsewhere. The initiative focuses on six ecosystems facing critical degradation that have significant societal value:

Chesapeake Bay;
Greater Yellowstone area;
Mojave Desert;
Platte River;
San Francisco Bay; and
the greater Everglades.

The initiative involves experts of all the USGS science disciplines in an effort to gain a systemwide understanding of the natural and human factors affecting ecosystems, as well as their response to adaptive management decisions. For example, on the Platte River, diversions and regulations of upstream flows have significantly altered the flow regime, creating changes in the river and riparian corridors, which now threaten several species of migratory birds. Integrated studies of the linkages between hydrology, river morphology, biological communities, and ecosystem processes are underway to develop approaches to sustain or restore the habitat of threatened and endangered species (http://access.usgs.gov/index.html).

Clearly the PES Initiative deserves a close look as a potential mechanism or channel for river science at the USGS, given its interdisciplinary nature, focus on ecosystems, and experience with rivers and their associated estuaries and wetlands. At present the initiative is moderate in size, but it has considerable potential for upscaling to include a larger number of projects with a variety of themes.

USGS ROLE IN RIVER SCIENCE

In Chapter 2 this report defines river science as an integrative multidisciplinary science, structured and conducted to develop a process-based, predictive understanding of the functions of river systems and their responses to current and projected natural variability and human activities. Many federal agencies have important roles in river science research arising from their mission and objectives. Those agencies are already making significant progress in addressing the multidisciplinary river science issues identified in Chapter 2. Likewise, the USGS role in river science should reflect its own history (Box 3-1), mandate, and capabilities, and these factors help define its responsibility within river science. Key attributes that help direct the USGS vision for future activities in river science are identified below.

Science Information Mission—Unique among federal agencies, the USGS has no regulatory, management, or advocacy mission. Instead, its mission is to provide science information for the nation. In that role the USGS has a well-deserved reputation as an impartial provider of science information and is recog-

BOX 3-1
History of Integrative River Science at the USGS

The USGS has a history of engaging in integrative river science. The root of many of today's most timely hydrologic and water resources management challenges reflect the integrative science that has been a hallmark of the USGS's water resources programs. Examples include G. K. Gilbert's pioneering scientific study of the movement and impacts of sediment in river systems draining hydraulically mined sediment areas in the Sierra Nevada (1914, 1917), which, while primarily focused on hydraulics, might be called the world's first environmental impact assessment. Other studies chronicled the significance of climatic drought (Hoyt, 1938) and topographic characteristics of drainage basins (Langbein, 1947). Much of the modern practice of stream restoration has its foundation in Leopold and Maddock's (1953) classical work on the hydraulic geometry of streams. Similarly, the emergence of modern groundwater hydrology and hydrogeology is based on the vision of integrative science championed at the USGS by Oscar Meinzer. The national focus on watershed management was presaged by investigations such as Wolman's (1955) classical study of Brandywine Creek. And the scientific heritage of the most timely issues in current watershed management can be found at the USGS in areas as diverse as the role of ephemeral streams in drainage networks (Leopold and Miller, 1956), ecohydrology (Leopold, 1960), and urban hydrology (Savini and Kammerer, 1961; Leopold, 1968), and in fundamental contributions to understanding sediment transport (Bagnold, 1966), channel form and pattern (Leopold and Wolman, 1957; Wolman and Leopold, 1957; Leopold et al., 1960; Bagnold, 1960; Langbein and Leopold, 1968), and statistical analysis of the quantity (Matalas, 1963) and quality of the nation's rivers (Smith et al., 1987; Gilroy et al., 1989).

nized for its rigorous process of scientific peer review. This lends credibility to USGS data and information on the nation's rivers, which is critical for resolving conflicts among competing and often contentious policy alternatives.

Multidisciplinary Staff—The USGS is a multidisciplinary earth science agency. It has the ability to bring together the scientific expertise among its many disciplines—hydrologists and geomorphologists, biologists and river ecologists, geologists, geographers, and geospatial information scientists—to formulate and execute an integrative river science initiative as envisioned in this report.

Data Collection and Monitoring Expertise—The USGS has a long heritage of serving the nation by collecting reliable scientific data and information. Its monitoring activities are distinguished for their scientific rigor and quality control. The USGS has also been a leader in the development of instrumentation for river monitoring. Furthermore, its data distribution infrastructure, including National Water Information System, National Biological Information Infrastructure, and The National Map, provides access to essential data resources needed for river research and management decisions.

National Science Synthesis Experience—The USGS has excelled in providing needed science synthesis on national issues related to natural resources. It has demonstrated its ability to formulate scientific plans to address information needs, execute monitoring programs to gather critical data, and carry out research that answers overarching questions and promotes scientific understanding.

Organizational Structure—The USGS structure can support river science at both local and national scales and encourages river science activities in all forms—bottom-up, top-down, and community-driven. For example, the Water Resources Discipline, with its science centers, Cooperative Water Program, and National Research Program, provides a framework for river science activities at a local scale, while informing a broader science synthesis at a national scale. Place-based multidisciplinary research activities, and the Biological Resources Discipline's collaborative efforts with university researchers and students at Cooperative Research Units, are also good templates for river science activities.

In line with these roles, strengths, and capabilities, the USGS is best poised of all the federal, state, and nongovernmental organizations to investigate rivers as *systems*, and determine how the critical system components relate to each other. Fulfilling this natural role will require (1) river science program elements in both crosscutting and focused scientific priority areas (Chapter 4), (2) river science monitoring and data management to support river science synthesis and information generation to support decision making (Chapter 5), and (3) institutional capacity building within the USGS, and programmatic integration and coordination across disciplines and existing program elements (Chapter 6). The specific recommendations for USGS activities in these areas are discussed in detail in the subsequent chapters.

CONCLUSION AND RECOMMENDATION

The USGS combines scientific, technical, and data collection expertise with a long history and exemplary reputation as the nation's source of unbiased policy-relevant information on earth system sciences. As an agency with no regulatory, management, or advocacy mission, and a history of doing basic science aimed at the public good, the USGS fills the important federal agency niche of providing the scientific connections between what is done in river science by other agencies, which are mostly projects driven by specific societal needs and often at the local scale. For these reasons the USGS is ideally suited and uniquely capable of serving the nation by prosecuting the kind of integrative multidisciplinary river science initiative envisioned in this report.

Recommendation: The USGS should establish a river science initiative to bring together disparate elements of the USGS to focus their efforts to deal with growing river science challenges. The ini-

tiative should build upon the USGS's history, mandate, and capabilities. It should take advantage of key attributes of the institution, such as its

(1) mission as provider of unbiased science information,
(2) multidisciplinary staff,
(3) data collection and monitoring expertise,
(4) experience in science synthesis at many scales, and
(5) organizational structure that combines national research programs with state-, watershed-, and university-based cooperative programs.

In carrying out the initiative, the USGS should closely coordinate with other federal agencies involved in river science and related activities.

4

Priority Areas for USGS River Science

This report has identified a compelling national need for an integrative river science, a science structured and conducted to develop a process-based predictive understanding of the functions of the nation's river systems and their responses to natural variability and the growing pervasive cumulative effects of human activities. This need is reflected in the growing number of conflicts that arise over the beneficial use of river resources and the environmental health of river ecosystems, as well as in Congress's repeated calls for the best available science to support policy and management decision making. As outlined in Chapter 3, the USGS role should reflect its own mandate and capabilities and build upon its core strengths. The design and activities of a USGS river science initiative should be guided by the overarching goal to provide unbiased, policy-relevant, science-based information to advance understanding and support decision making for the nation's river systems.

Neither the USGS nor any other agency or organization can carry out all the science involved with water, sediment, chemical constituents, and organic material in river systems and their ecosystems. To this end, USGS river science priorities must be directed toward prioritizing research with respect to funding sources that can be brought to bear, answering the key questions of national interest and those the USGS is best positioned to address, and leveraging USGS research strengths with the needs of other federal agencies.

Of the many river science questions, the committee has identified specific science priority areas where the USGS can contribute to the national understanding of rivers. These priority areas are derived essentially from the intersection of society's needs, as described in Chapters 1 and 2, with the USGS's capacities, as described substantively in Chapter 3. Each of these priority areas addresses actions that would improve the scientific foundation and enhance the scope of river science.

The first two science priority areas are crosscutting activities that would strengthen the holistic river science approach. These translate into recommendations for the USGS to (1) conduct a national inventory to survey and map the nation's stream and river systems according to key landscape features that act as determinants of hydrologic, geomorphic, and ecological processes in streams and rivers and (2) develop conceptual and predictive models that could be used to couple surface water, groundwater, geochemistry, and sediment fluxes, and to quantify ecological responses.

Although we pose these crosscutting science priority areas individually, there is great potential for these activities to enhance each other. A national river science survey would provide a framework or template through which the multiple disciplines within river science could communicate both monitoring information and model results about rivers across the landscape. Additionally, modeling river processes can help indicate the key variables that are most important to monitor and synthesize nationally. Thus, these activities would underpin the USGS's science contribution to a broad national effort in river science.

In addition to suggesting ways to enhance the interdisciplinary river science vision, the committee has identified three areas of river science for which improved knowledge and understanding is needed, and for which the USGS can play a leading role. These are (1) the characterization of environmental flows in rivers (flow levels and patterns necessary to maintain healthy aquatic ecosystems), (2) basic research, synthesis, and monitoring of fluxes (bed load and suspended load) and their relation to channel dynamics, and (3) full integration of floodplain processes and groundwater hydrology as a basic component of river systems. Investigations into each of these topical science activities are more targeted, both in their geographic extent and specific processes monitored, than the crosscutting activities, although each of these science activities would involve enhanced monitoring and modeling and would be key components of the overall river science framework.

In each section below, the committee outlines the science recommendation and then expands on this recommendation by addressing four overarching questions:

1. Why is the recommendation in the national interest?
2. Why should the USGS be involved in this river science issue?
3. What is a compelling problem related to the recommendation?
4. What are some examples on how the USGS might do this?

CROSSCUTTING SCIENCE PRIORITY AREAS

Surveying and Synthesizing

Recommendation: The USGS should survey and map the nation's stream and river systems according to the key physical and landscape features that act as determinants of hydrologic, geomorphic, and ecological processes in streams and rivers. This synthesis will provide a scientific baseline that can be used to support many regional-scale river science questions and afford geographic information of use to state and federal agencies, academia, and the public.

The form of rivers and their internal dynamics are driven by a diversity of processes that occur throughout the watersheds they drain. The defining characteristics of a river—its hydrologic regime, sediment load, nutrient assimilation, and ecology—reflect the intimate connection of the river network to the surrounding landscape. Thus rivers integrate the climatic, geologic, and land-use processes in their watersheds. River science seeks to understand how streams and rivers are influenced by these complex watershed processes and therefore gain a better understanding of how they might respond to natural and human-influenced environmental changes.

Across the nation, there are large, regional gradients in climate, geology, topography, land cover, and human impacts on rivers. This extensive variation makes meaningful generalizations about how streams and rivers function challenging. It also complicates how information collected in one river can be appropriately transferred to another geographically distant river. Yet obtaining this type of knowledge is fundamental to attaining both regional-scale understandings and national synthesis in river science. Determining regionally representative monitoring sites and criteria, so knowledge gained from those sites can be transferable, requires understanding the variety of river settings within regions and across the nation. Therefore, a survey and synthesis of existing information is needed to generate a spatial framework or baseline map that can be used to organize empirical data, extrapolate information to locations lacking data, and stratify variations in river processes to assist in the selection of appropriate monitoring or reference sites for regional studies. This framework should flexibly characterize spatial variation in key landscape processes that control many instream river processes. Such a mapping project would produce a valuable tool that other agencies and the public would benefit from, and it would integrate information across agencies (e.g., riparian [USDA], dams [USBR, USACE], water quality [EPA], and water quantity [USGS]).

The USGS should consider stratifying the nation's rivers at a reach scale based on both the natural setting of a river (comprising climate, topography, soils, gradient, and geology) and the type and magnitude of human alteration (comprising upstream diversions and impoundments and land-use characteristics) that dictate key physical and chemical processes that are known to drive the ecological structure and function of river channels and their riparian buffers. Rather than a comprehensive new surveying and mapping exercise, this could be a preliminary stratification based upon national-scale, spatial datasets that are readily available and that can be analyzed quickly using existing Geographic Information System (GIS) technology.

Why Is the Recommendation in the National Interest?

River science and management questions arise in a diversity of settings, and the USGS is called upon to provide information in all these settings. Additionally, many questions in river science do not require detailed process-based information (fine-grained data expensive to acquire at large spatial extents such as synoptic studies). Therefore, to ensure that monitoring information is transferable to all locations of interest, it is important that USGS river science research cover the full range of river settings and processes. Survey information on river attributes, which is used to stratify river reaches, is a prerequisite to ensure coverage and thus support the transferability of river science knowledge. The survey to support stream reach stratification will also produce a rich set of attributes that will be of value to federal and state agencies involved with river use, water-quality protection, and restoration. Applications of such a baseline map include identifying river reaches having similar (or different) attributes that influence ecological condition, flood risk, landslide potential, invasive species spread, water-quality impairments, and many others. Evaluating changes in our river systems in response to climatic, regulatory, and other anthropogenic impacts is clearly a national issue.

This attribute-rich, spatial coverage was already suggested as a basis for a sampling design in the context of the National Streamflow Information Program streamgaging network (NRC, 2004d). Many elements necessary for stratification of the nation's rivers at a reach scale are present in the National Hydrography Dataset products that are under development in partnership with the EPA (NHDPlus); (http://www.horizon-systems.com/ NHDPlus/index.htm).

Why Should the USGS Be Involved in This River Science Issue?

The USGS is the nation's mapping agency and is therefore uniquely capable of integrating the information necessary to stratify stream reaches. Mapping attributes associated with stream reaches would draw heavily on USGS resources, such as the national elevation dataset and its derivatives, national hydrography dataset, geology, land use, and land cover. Further, under the direction of both the legislative and executive branches, the USGS has recently been increasing its efforts to examine and characterize water availability in the nation. This mapping effort would therefore provide an opportunity to integrate information on the nation's water infrastructure (e.g., dams, diversion structures, groundwater pumping) into a comrehensive river science perspective that would allow visualization of the human imprint on rivers and streams at the regional to national scale.

What Is a Compelling Problem Related to the Recommendation?

Like topographic and geologic maps, the spatial framework envisioned here will provide a foundation upon which a wide variety of science and management applications in river science would be based. In this case, the nation needs a way to describe the multifaceted characteristics of river reaches that does not yet exist. Streams and rivers are complex integrators of multiple watershed processes, and mapping the overlay of the many factors (both natural and anthropogenic) that drive riverine processes is a necessary first step toward erecting a national framework for river science that will support many issues in river science of national importance. Such maps would be useful for identifying or stratifying reaches (or subwatersheds) with similar or dissimilar potential in terms of environmental responses to natural or anthropogenic drivers.

For example, many river science questions emerge at the regional scale where spatial distribution of resources must be assessed. This requires sampling designs that accurately and adequately ensure that samples are representative. A GIS-based map of stream and river reaches will provide end users the flexibility to define and develop a map from some combination of drivers to address regional-scale questions.

What Are Some Examples on How the USGS Might Do This?

Because rivers integrate processes across diverse environments and multiple scales (i.e., the flow regime in rivers depends on the watershed's climate, topography, geology, land cover, and river size), a scientific understanding of river processes requires a framework that incorporates these differences. Identifying this conceptual framework would allow for site matching, a method for identifying where environmental conditions are similar, implying similar response in riverine function. Such a framework would allow for observations to be appropriately interpreted and differences meaningfully studied. Frameworks similar in principle to the proposed mapping program have been undertaken as *classification* systems, which are typically based on one or two important physical-chemical drivers (e.g., flow regime, channel geomorphology). These classification systems are incomplete and may not be adequate for the purposes of interdisciplinary river science at the national scale.

The USGS should review existing river classification systems to identify the driving variables that determine the range of physical, chemical, and biological features of streams and rivers. These features can be attributed to river reaches nationally and thus serve as a comprehensive inventory of the spatial distribution of combinations of key environmental drivers of river structure and function. This richly detailed map will serve as the underpinning reference for USGS-based river science and observations, and it will provide a point of reference for process study and scientific hypothesis testing. Furthermore, this information will be available to a diversity of users (government, academia, and the public), some of whom may wish to use this information to develop question-specific classification systems.

An excellent example of a national river mapping program is the New Zealand River Environment Classification (REC) (Snelder and Biggs, 2002; Snelder et al., 2004, 2005). The REC classifies individual river reaches in terms of physical factors: climate, source of streamflow, geology, land cover, position of the reach in the river network, and channel (and valley) shape. These factors are known to control important river processes, such as flow regime, temperature regime, rates of land soil erosion and nutrient release, instream flux and storage of sediment, and local habitat structure. These factors are also hierarchically related (e.g., climate influences whole watersheds whereas channel form is a very local factor). This hierarchical framework allows maps to be created at different scales of resolution, from whole watershed maps of climate and flow regime to reach-scale maps that show how all six factors interact. These maps are provided as a GIS layer (Figure 4-1). This tool has been used in New Zealand to test hypotheses about how variations in biological and chemical water quality are related to reach-scale classes, and it has been shown to perform better than more traditional and less process-based classifications such as ecoregions (Snelder et al., 2004). The power of the approach is the user-defined ability to generate maps that include different driving environmental factors at different degrees of spatial resolution to test specific hypotheses or to identify similar types of habitat for monitoring or resource evaluation.

In the context of USGS river science, developing a comprehensive set of map layers based on key environmental factors would provide a tremendous resource to a number of potential end users; the USGS would not necessarily be compelled to develop a classification system per se. USGS data resources and mapping capability are well suited to the task of developing and implementing this mapping program. Given the many and diverse applications that such a map could serve, developing such a map should involve broad participation with as many sectors of the river science community as possible. Indeed, many data components of this national synthesis exist at USGS and elsewhere (e.g., the streamgaging network, regional hydrologic analysis of flows [peaks and flow statistics], the national hydrography layer, the USACE national inventory of dams, land-cover maps, and geologic maps).

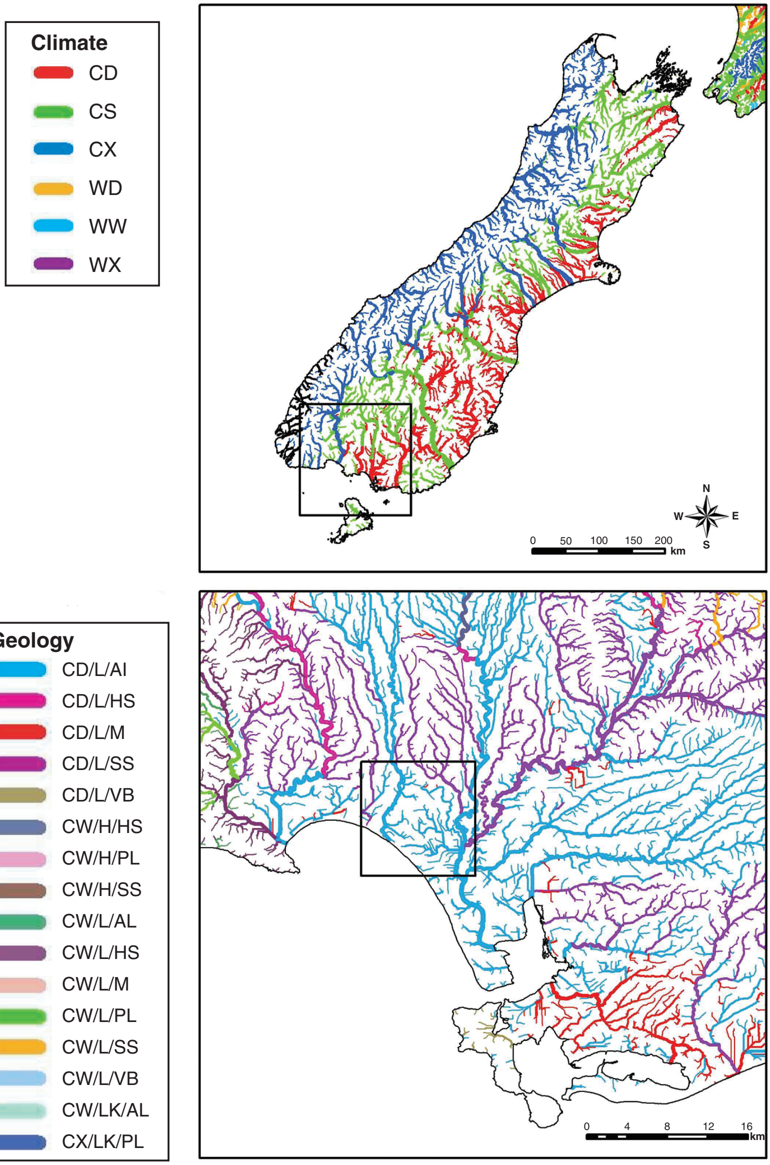


FIGURE 4-1 A classification of the South Island of New Zealand showing classes at the climate level of the River Environment Classification, as well as zooming to three progressively more detailed scales that demonstrate sources of flow, geology, and landforms respectively. SOURCE: Reprinted, with permission, from Snelder and Biggs (2002). © 2002 by the American Water Resources Association.

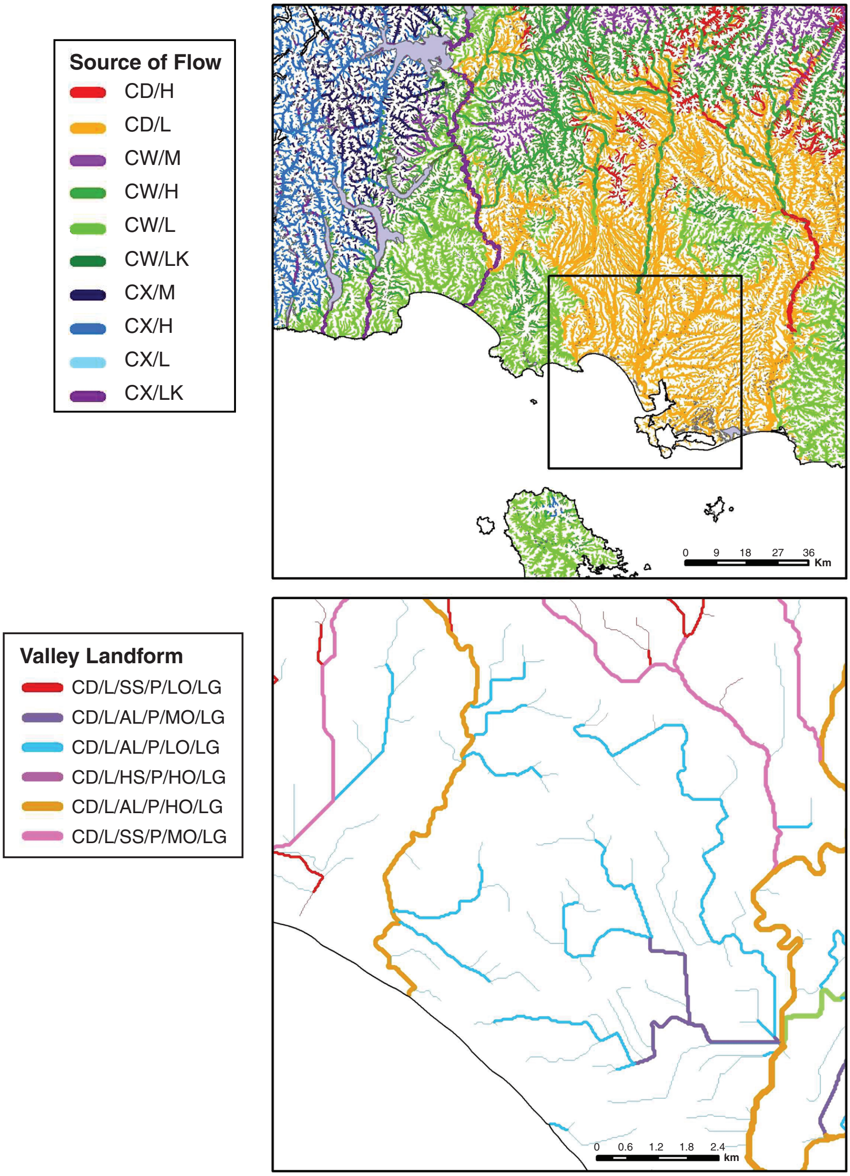


FIGURE 4-1 Continued

Modeling River Processes

Recommendation: The USGS should add capacity in developing predictive models, especially models that simulate interactions between physical-biological processes, including transport and transformation of chemical constituents, pollutants, and sediment. These tools provide the underpinning for predicting ecological change.

Quantitative models that integrate physical, chemical, and biological processes can provide detailed information on pathways and interactions that are difficult to measure directly in the field or are nonstationary in time. Point measurements and synoptic surveys of hydroecological processes are essential components of river science; however, the measurements needed to describe these interactions are often time consuming and costly. Thus there is a growing need for numerical models and instrumentation that can be used in place of labor-intensive field surveys. Additionally, these models can be used as tools to compliment and help focus monitoring efforts, thus allowing researchers to investigate across greater spatial extents.

Why Is the Recommendation in the National Interest?

In addition to integrating field studies and minimizing costly, labor-intensive surveys, models have predictive ability that if used appropriately, can provide insight on physical-biological responses to changes that are likely to occur in the future. For example,

- Riverine habitats that are used by fish and other aquatic organisms are formed and maintained by a range of flow conditions. A critical need exists for the development of more advanced ecohydraulic models that focus on the structure of flows, and that can be used to investigate the physical-ecological response of river systems to changes in flow regime.
- Water flowing within a river channel exchanges with water present in the streambed and the banks and floodplain. This flow can be a source or sink for nutrients used by organisms at all trophic levels, in addition to providing "bank storage" that mitigates flooding and provides baseflow to the channel.

Why Should the USGS Be Involved in This River Science Issue?

The USGS has a long history of developing quantitative process-based models of both heuristic and real-world hydraulic systems. Suites of publicly available software are used to model a wide range of processes, including runoff in large river basins, flow and sediment transport in rivers and estuaries, and groundwater transport of solutes and pollutants in aquifers. Of these, the groundwater and multiphase solute transport models are industry standards (e.g., MODFLOW and SUTRA). USGS researchers also have a collective knowledge and experience in model calibration. The network of over 7000 streamflow-gaging stations, with standardized and quality-controlled streamflow and water-quality data, contributes to the USGS's development and testing of numerical models of streamflow, sediment transport, nutrient cycling, and ecosystem responses to variations in water-quality constituents, such as dissolved oxygen, temperature, and salinity.

A number of USGS researchers are illustrating the strengths and potential applications of integrated multicomponent models. Some examples include mapping of land cover and terrain characteristics for use in modeling sediment supply and contaminant transport to a reservoir in the foothills of the Sierra Nevada; estimation of water supply, aquifer storage, and water reuse within the highly urbanized watershed of the Santa Ana River in southern California; and coupling of hydraulic habitat models to assess the effects of channel modification on fish habitat in the upper Yellowstone River. Recently, USGS scientists coupled their groundwater flow model, MODFLOW, with BRANCH, a surface-water simulation program to simulate streamflow with both regular and irregular channel cross sections. This powerful model calculates temporal changes in water levels, flow discharges, and velocities in a spatially explicit channel network and is especially suited to evaluate streamflow in upland rivers with backwaters and where discharge is highly regulated. BRANCH also is used to explore the interaction of freshwater inflows, tidal action, and changing weather conditions.

Much of the support for USGS investigations and data acquisition activities comes from federal and nonfederal agency cooperators. The breadth of USGS activities and their capabilities in modeling are strengthened by the diversity of the cooperator base. In addition to federal agencies (e.g., COE, EPA, USFWS), the cooperators include state agencies or municipalities that often lack the resources and/or expertise to undertake specific projects. The USGS has unique capabilities in combining its expertise in mapping, modeling, and data serving to provide cooperators with near real-time information for a range of needs, including flood forecasting, specification of streamflows for environmental maintenance, and the development and management of groundwater resources.

What Is a Compelling Problem Related to the Recommendation?

Almost all aspects of river science can be addressed using process-based models developed from strong conceptual models. Consider, for example, the growing need to manage water for an expanding number of uses, including uses that were unforeseen 40 to 50 years ago, such as environmental maintenance flows. The key parts of this problem are (1) knowing how much water currently exists within a surface-water and groundwater system, and (2) understanding the hydrology of the system well enough to predict the response to changes in water supply and/or water use. Inferences drawn from field observations and data collected over a period of years are often used to address the first part of the problem, whereas modeling is the most practical and efficient way to address the second part of the problem. The computational efficiency and accessibility of models has changed significantly in the last decade, and probably most river scientists see modeling as a key part of their research. The challenge in the near term is not really in the development or use of hydrologic models for specific purposes but rather in the refinement and linking of existing models to address multi-objective water management strategies.

Recently, the USGS and others have been promoting the development of an open-source numerical model for sediment transport in coastal regions, named the Community Coastal Sediment Transport Model (http://woodshole.er.usgs.gov/project-pages/sediment-transport/). In a similar way, the USGS could also play a leadership role in developing a Community River Sediment Transport Model in collaboration with other federal agencies, academic institutions, and private industry, with the goal of adopting and/or developing one or more models for use as scientific tools by the river science community and government agencies responsible for river management.

What Are Some Examples of How the USGS Might Do This?

An example that illustrates the potential of integrated modeling can be found in the Klamath River Basin, where the USGS is involved in broad-based efforts to better manage water resources within this river system. The USGS and the Oregon Water Resources Department are developing a regional groundwater flow model to simulate aquifer responses to changes in agricultural use and variations in climate. Additional work is being done in the Klamath basin to assess the feasibility of using a "water bank" to store surplus water in wet years to meet biological flow requirements in dry years (http://oregon.usgs.gov). Statistical models coupling measurements of precipitation, air temperature, snowwater equivalence (SWE), and groundwater levels are being developed to reduce uncertainties in streamflow forecasts for upper Klamath Lake (http://or.water.usgs.gov/klamath/).

Hydrologists from Utah State University are using the USGS Multidimensional Surface Water Modeling System (MSWMS) to evaluate habitat suitability for Chinook salmon and Steelhead along ~ 300 km of the Klamath River. In related work USGS scientists from the Fort Collins and Portland Science Centers have linked a water-resource planning model to a water-quality model to simulate seasonal changes in water temperatures with and without the dams that are currently in place.

Because river science is inherently integrated, promoting the use and development of these integrated models fits naturally into its future direction and vision. Having the tools to better investigate the integrated system through coupling models of surface-water supply, groundwater extraction, and water quality would benefit the nation in multiple ways. For example, if there were an improved understanding of the integrated system, controversies like the one which erupted in 2001 when water deliveries to farmers served by the Klamath Project were cut off because of potential biological impacts of low water levels (NRC, 2004b) could conceivably be avoided.

TOPICAL SCIENCE PRIORITY AREAS

Environmental Flows and River Restoration

Recommendation: The USGS should develop the means to characterize environmental flows in rivers by developing quantitative models that link changes in the ecological structure and function of river ecosystems (aquatic and riparian) to management-scale changes in river flow regimes.

Recommendation: The USGS should, in cooperation with and support of other federal agencies involved in restoration, serve as a leader to evaluate the scientific effectiveness of river restoration approaches to achieve their goals, synthesizing results from past restoration efforts and designing standard protocols for the monitoring and assessment of river restoration projects.

Water supply demands and landscape alterations have put unprecedented pressure on the nation's rivers. Dams, levees, other forms of water development, or the clearing and paving of substantial portions of watersheds have significantly altered most of the nation's non-wadeable rivers. Dams have led to an increase in water storage and a reduction in seasonal flows in rivers, which have altered both the connectivity and flow regimes of rivers. Human activities, including agriculture and development, have introduced large amounts of sediment and contaminants into streams. Direct manipulation of channels and floodplains and the construction of levees have led to the loss of habitat and flood storage capacity. In many areas, land clearing and urbanization have caused an increase in the magnitude of floods and a decrease in baseflows. Channels have been eroded and down-cut, leading to a decline in river biota and leaving riparian flora hydrologically isolated.

A fundamental scientific challenge underlying many of the issues in river science is a better quantitative understanding of how rivers respond physically and biologically to these alterations. The basic fluvial processes of water flux and sediment transport interact to create the structure of physical habitat and the dynamics of habitat change, which create the ecological template of the river system. An alteration in the flow regime of a river modifies these fluvial processes and typically results in ecological adjustments to the new, altered physical habitat structure and dynamics. A specific, emerging area of river ecology, called environmental flows, attempts to understand the ecological responses to flow alteration. Environmental flows are broadly defined as those flow levels and patterns (e.g., magnitude, timing, and variability) necessary to maintain the ecological processes, biodiversity, and associated goods and services that are characteristic of a self-sustaining river ecosystem (Arthington et al., 2006).

Historically, the emphasis has been on the flow-dependent habitat needs of a particular, often socially valued, species (e.g., trout). More recently, however, efforts have become focused on trying to model or understand responses of multispecies ecological communities, both riparian and aquatic, an endeavor often made very difficult due to the incomplete knowledge of environmental flows and the habitat needs of many constituent species.

By improving this scientific information and providing this knowledge to decisionmakers, the USGS can play a critical role in developing science-based policies that influence environmental flows. Finding a balance between ecosystems' needs to keep water in rivers versus society's needs to modify or extract the flow of water in rivers is one of the great natural resource challenges facing policy makers in the United States. Increasingly, policy makers must seek a balance between ecosystems' needs for adequate environmental flows versus society's needs for water abstraction or storage for agriculture and development (Poff et al., 2003). The USGS can help in addressing these challenges by applying the latest knowledge and technology to answer many pressing scientific questions, for example:

- How much water and with what variation over time needs to be left in rivers so they have a reasonable chance of being self-sustaining and providing important goods and services, such as protection of native species, food production, and waste assimilation?
- How does the rate of groundwater extraction influence the susceptibility of riparian corridors to invasion by non-native, nuisance plant species that may reduce habitat quality for terrestrial species?
- Can restoring instream habitat heterogeneity alone ameliorate the negative effects of flow alterations on many aquatic and riparian species?

Why Is the Recommendation in the National Interest?

These two recommendations are in the national interest because they will provide objective scientific information to inform science-based resource management decisions that address the increasing human demand for fresh water and society's interest in maintaining self-sustaining aquatic ecosystems. The nation is currently spending billions on restoration and rehabilitation projects. Currently we do not know if this is a good investment or if the highly variable approaches are scientifically sound. Most of the thousands of recorded river restoration projects in the United States have been monitored poorly, if at all (Bernhardt et al., 2005). Future restoration projects, if they are to be successful, will require justification using empirical, quantitative measures of ecosystem responses that provide confirmation and quantification of their ecosystem services (Rood et al., 2005; Sweeney et al., 2004). Adaptively managed, reach-level river and riparian systems valued for their ecological services will require long-term monitoring of the flow regime, groundwater activity, primary productivity, and habitat diversity in targeted locations.

Quantitative models relating ecological function to flow regimes will allow natural resource managers and citizens to forecast the impacts of proposed water management decisions. This will enhance the ability to make scientifically informed decisions. For those riverine ecosystems that are already degraded, restoration that is guided by the latest scientific knowledge will promote recovery of natural resources critical to the control of floods, the health of fisheries, and the provision of clean water. Currently, citizens, restoration practitioners, and natural resource managers are seeking scientific information on the effects of restoration issues as diverse as dam removal and reconfiguration of channels to protect infrastructure. By synthesizing existing information, testing various restoration approaches for effectiveness, and providing the resulting data to the public, the USGS can contribute to the wise use of scarce restoration dollars throughout the United States.

Why Should the USGS Be Involved in This River Science Issue?

These recommendations apply to the USGS because they have the existing knowledge, talent, and ability to address complex ecological river science issues. The USGS has extensive regional and national databases on flow-biota relationships from small streams to large rivers. Furthermore, the USGS is able to use this data to leverage with their extensive expertise in both hydrologic modeling and supporting interdisciplinary research in hydroecology. Specifically, the USGS is poised to address environmental flow and restoration questions through focused work in two broad arenas that are themselves intertwined: (1) developing quantitative models that link physical and ecological processes in rivers and (2) advancing the scientific basis of river restoration.

Any study of environmental systems must consider multiple mechanisms and their interactions over space and time. Mathematical and statistical modeling provides a formal and rigorous means of describing and evaluating the functional consequences of such interactions. Models can provide vital information to those who manage river systems and those who design and implement river restoration. Conversely, studies of riverine responses to management and restoration actions can inform and help refine models.

What Is a Compelling Problem Related to the Recommendation?

The building of dams severely alters environmental flows and presents many challenges for restoration. The presence of dams fragments populations of plants and animals with local extirpations being quite common, particularly in the western United States. For species populations below dams, the flow regime fundamentally differs from its historic pattern. Many organisms have been unable to survive and reproduce without the seasonal changes in flow that the river had always provided and their life cycles depend on. Ecological processes such as primary production, decomposition, and nutrient cycling that support river food webs and contribute to water purification have also been strongly modified by alterations to river flow regimes. All of these problems contribute to a growing concern about the ecological sustainability of our nation's rivers and streams, and society has shown a strong interest in responding through scientifically informed management of our water resources.

What Are Some Examples on How the USGS Might Do This?

A paradigm in ecology-based water management is that it is necessary to mimic a natural flow regime (i.e., ecosystem processes will be most self-sustaining when the flow regime is similar to a natural state) (Poff et al., 1997; Bunn and Arthington, 2002; Baron et al., 2002, 2003). Characterization of flow impairment is often based on calculating the deviation of current flow regimes from some pre-impact, historical reference using any number of indices or metrics that capture the natural range of variation in flow thought to influence ecological processes most directly. One well-known and widely used approach is the Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996). IHA is a software program that was designed for The Nature Conservancy for use in both research and management and offers an example of a method of developing environmental flow recommendations for managers (http://www.nature.org/initiatives/freshwater/conservationtools/).

The conceptual principles of the natural flow regime have gained wide acceptance in the United States (and elsewhere), and some states are now actively implementing these principles to set standards for flow regime alteration. For example, the state of New Jersey is collaborating with the USGS to develop a statewide streamflow classification to be used to guide land-use practices that influence stream runoff. However, despite much progress in this area, as the conceptual basis for flow alteration has become accepted, there is a growing societal expectation for a more specific articulation of just *how much* flow restoration is needed to achieve *what degree* of ecological gain (Poff et al., 2003). These questions are difficult because they often require a site-specific understanding of hydrologic-geomorphic-ecological relationships. Nonetheless, these questions are central to river science, and the USGS is well positioned to contribute to their resolution through research and collaboration with other partner agencies, academia, and nongovernmental organizations.

The USGS is already involved in hydroecological research to some extent. The Biological Resources Discipline (BRD) in Columbia, Missouri, has projects on the Missouri River to examine relationships between channel flows and fish species. The BRD in Fort Collins, Colorado, has developed great expertise in articulating the relationships between river flow and riparian zones in large regulated rivers such as the upper Missouri and the Gunnison River flowing through Black Canyon of the Gunnison National Park. Also, the National Water-Quality Assessment (NAWQA) program is undertaking studies to quantify relationships between degrees of flow alteration and instream biological metrics (e.g., macroinvertebrate and fish species communities) for many of their study units across the United States. These efforts indicate that the USGS has the in-house capacity to develop further this important hydroecological focus within a river science initiative. For example, some combination of these comparative approaches could be applied more broadly to compare hydroecological function among large rivers with varying levels of flow regulation—from highly regulated (e.g., Columbia, Colorado, Missouri) to less regulated (e.g., Yukon, Upper Mississippi, Ohio, Hudson).

Further, intensive studies undertaken in partnership with other agencies (Box 4-1) present an opportunity to develop coupled hydrologic-ecological models. For example, there are now many large, expensive river restoration projects that are motivated by the recognition that the river flow regime needs to be restored to a more natural condition to improve ecosystem function, such as in the Grand Canyon (NRC, 1996). On the Rio Grande the USGS is one of six federal agencies in a consortium of river flow managing agencies on the Upper Rio Grande Water Operations Model (http://www.spa.usace. army.mil/urgwom/). The USGS has also collaborated with the New Jersey Department of Environmental Protection to develop a methodology to estimate flows that would "sustain healthy stream ecology" (http://nj.usgs.gov/special/ ecological_flow/). Their objective is to provide a technical basis for planning and regulatory decisions that affect instream flows and associated aquatic ecosystems on a statewide basis. In these multiagency projects where management of the river flow regime is being considered, the USGS should take a lead in defining key hydrologic-ecological linkages and thus present the objective understanding of how ecological processes respond to hydrologic alterations across a range of possible water management options.

In leading efforts to guide restoration and to develop quantitative models to understand (and predict) the river's ecological response, there are several allied roles the USGS should take on. First, the USGS should play a lead role in coordinating efforts and forging partnerships to develop the interdisciplinary river science research programs. Hydrologists, biologists, geomorphologists, engineers, and social scientists will need to work as teams to identify the new

BOX 4-1
Upper San Pedro River:
Interagency Efforts on Environmental Flow

The San Pedro River flows north from Cananea, Mexico, to the Gila River. In 1988, Congress designated 40 miles of the river corridor, which have an intact southwestern riparian habitat, as the San Pedro Riparian National Conservation Area (SPRNCA). This special designation reflects its status as a regionally critical resource (http://www.ars.usda.gov/research/projects/projects.htm). Currently 70,000 people share the Sierra subwatershed with SPRNCA. The majority of the population depends on groundwater wells, intercepting the groundwater discharge to San Pedro River. These withdrawals intercept the subsurface water flowing to the SPRNCA and the river, threatening the water supply available to the riparian area (http://az.water.usgs.gov/projects/AZ17801.htm). Without an adequate long-term water supply, neither the people of the area nor the river will thrive.

Twenty-one agencies (federal, state, academic, and nongovernmental organizations, along with the USGS) have formed a consortium, the Upper San Pedro Partnership, to work together to develop a river management plan (http://www.usppartnership.com). The partnership's goal is to "ensure an adequate long-term groundwater supply is available to meet the reasonable needs of both the area's residents and property owners (current and future) and the San Pedro Riparian National Conservation Area."

Key research needs include developing groundwater models (to describe how the groundwater system is related to the river and to understand the effects water uses have on the entire system); a decision support system (to integrate available information into a computer program that allows decision makers to see the potential impact of specific water management scenarios); and a water needs study (to find out how much water the trees and other vegetation near the river actually use and will continue to need to stay healthy). The USGS is a prime player in the partnership and is listed in the 2005 Water Management and Conservation Plan (http://www.usppartnership.com/documents/Working%20Plan%202005%20(Final).pdf). In 2005, the need for this effort became particularly evident when the river dried out at the Charleston Narrows for 13 days in early July. It was the first time the river's flow had ceased there since monitoring began in 1904.

knowledge that is needed and to determine how best to obtain and synthesize the required data. Ideally, if the key ecological processes that support ecological patterns (e.g., distribution and abundance of fish) are understood and can be modeled quantitatively as a function of physical factors, managers will have the knowledge they need to restore or preserve river ecosystems. Additionally, such models can be subjected to sensitivity analyses to evaluate the uncertainty associated with differential restoration of the magnitude, frequency, duration, and timing of a river's flow regime. These kinds of hydrologic-ecological models are needed not only for dam reoperation studies but also for predicting the ecological responses to dam removal and to river dewatering due to conjunctive use (groundwater pumping).

Second, the USGS should play a lead role in maintaining a monitoring baseline to assist adaptive management. The agency is already the leader in hydrological monitoring and should become more active in leading efforts to identify what types of ecological monitoring efforts are needed to inform models and advance integrative river science.

Colocation of biological monitoring networks with hydrological networks would represent a major step forward in developing the needed databases.

Sediment Transport and Geomorphology

Recommendation: The USGS should increase its efforts to improve the understanding of sediment transport and river geomorphology in the nation's rivers. By advancing basic research on sediment-transport processes, and by developing new technologies for measuring fluxes of bed load, suspended load, and wash load, the USGS can provide key information and tools to predict channel morphodynamics, develop methods to mitigate future problems arising from sediment movement, and play a guiding role in multiagency efforts to deal with the increasingly important national sediment challenges.

Studying river sedimentation involves the erosion, transport, and deposition of sediments in fluvial systems. Sediment transport mechanisms depend on sediment size as well as multiple physical processes, which are currently understood to varying degrees. Bed sediments can be transported along the bottom as bed load by fluid drag or in suspension by turbulence. In gravel-bed streams, most sediment is transported as bed load, while in sand-bed streams materials can be transported as both bed and suspended load. It is well known that sediments transported as wash load—the finest fraction of sediments transported in suspension by a river (less than 62 microns)—tend to be deposited in floodplains where vegetation reduces the flow velocity enough to promote settling. While bed load and suspended load are direct functions of the transport capacity of a given stream, the wash load is determined mainly by the amount of clay- and silt-size material produced by a given watershed.

The USGS could make an important contribution to river science by measuring these sediment fluxes in rivers. Because many pollutants can attach to fine sediment particles, understanding this conspicuous sediment transport mechanism is important. Furthermore, analyzing the geochemistry of these fine-grained sediments can help determine watershed conditions (the wash load can be analyzed to provide a watershed's fingerprint) as well as the effect of land-use management. Therefore, a monitoring program should include observations of bed load, suspended load, and wash load as well as flow velocity and water temperatures associated with such sediment transport conditions. A recently conducted sediment budget for the Illinois River (Demissie et al., 2004) shows that sediment deposition has reduced the water storage capacity of the Peoria Lakes to approximately 20 percent of their original capacity. This in turn has affected the navigation conditions of the Illinois River, resulting in millions of dollars spent on sediment dredging every year in order to maintain the necessary water depths for barge traffic. This is a good example of the need for having real-time monitoring of sediment fluxes in river systems so that effective river management strategies can be analyzed and implemented.

The geomorphic effects of land use, dams, and reservoirs and their consequent impacts on the region's ecology also vary widely, depending on the size of the reservoir, dam operations, and the river's location with respect to water and sediment sources and the nature of other water control structures. In the Platte River basin, for example, annual peak flows have been greatly reduced, leading to channel narrowing that may have adversely affected nesting habitat for the sandhill crane and the whooping crane. In the Colorado River downstream of Glen Canyon Dam, the channel is depleted of sediment, resulting in persistent erosion of beaches and sand bars that serve as habitat for threatened and/or endangered native warm water fishes. On the lower Mississippi, lack of sediment transport into the floodplain has resulted in the continuous degradation of the Mississippi Delta, decimating marsh lands that are the main source of natural protection against the devastating effects of hurricanes such as Katrina. Future decisions on how to manage the delta area will depend largely on how well the cycle of sediment erosion, transport, and deposition is assessed and on what predictive tools are available for the evaluation of different alternatives.

Rivers are constantly changing—shaping and reshaping their flow paths—yet there is still a fundamental lack of knowledge of how rivers evolve in time and space. Meandering streams have more ecological diversity than straight channels while pools and riffles in gravel-bed streams and dunes in large sand-bed streams seem to promote benthic conditions appropriate for habitat growth. The degrees of morphological complexity also determine alluvial flow resistance and thus flood stages. In rivers like the Missouri, temperature changes are known to affect bed morphology, but such effect has yet to be quantified to improve management strategies.

The USGS should play a leading role in the emerging area of river morphodynamics, and in the research and development of sediment measurement technology to assess sediment fluxes, grain-size distributions, geochemistry, and bed morphology. The USGS has already developed a strong research and development program in hydroacoustics for flow measurement and should continue to move technology forward in developing a similar program on sediment measurement technology. To this end, strong consideration should be given to implementation of the USGS' proposed National Sediment Monitoring Program. Collaboration with industry and universities is also encouraged since this could help the USGS in developing and testing new sediment measuring technologies. At a workshop organized by the USGS in 1998, the most promising sediment measurement technologies were discussed and several proposals were presented for new developments (http://water.usgs.gov/osw/techniques/sedtech21/).

Why Is the Recommendation in the National Interest?

Because of the construction and operation of about 75,000 reservoirs and other structures, processes that supply sediment from watersheds have become increasingly disconnected from the processes that transport sediment in rivers and form delta wetlands and shape estuaries. Therefore, in most major river basins and their deltas and estuaries in the United States, reservoirs, dams, levees, or other structures now interrupt the orderly flow of water, sediment, and nutrients. This typically has led to changes in channel morphology because channels tend to adjust their width and depth downstream to convey the water and sediment supplied. It is clear that river, coastal, and estuarine morphodynamics are topics of national interest where the USGS could play a leadership role (Parker and Garcia, 2006).

To understand the effects of human alterations and better manage rivers, sediment budgets are badly needed for most of the major river systems in the country. For example, we know little about how much sediment makes it to the Gulf of Mexico via the Mississippi river or how much sediment is retained by the dams along the Missouri River (Figure 4-2). Yet, the successful development of delta management strategies hinges largely on our ability to measure sediment loads along a river system. The Sacramento-San Joaquin Delta is another good example of a sediment-starved system where management decisions would benefit greatly from basic knowledge of sediment transport. This region has many levees that were built by early settlers that are now privately owned and unmaintained. Therefore, there is an ever increasing danger that these structures are unsuitable to withstand future stresses, and flooding in this heavily populated region would be a serious disaster threat.

Stream channels along the coasts have also experienced both the effects of changes in sediment supply due to land clearing for agriculture and construction of farm ponds, and the effects of changes in the hydrograph due to urbanization. Understanding these changes and thus being better able to predict the erosion, transport, and fate of contaminated sediments would be highly valuable to the nation.

Rivers in urban areas are now being used more by the public for recreational opportunities. The Chicago River is a good example of a stream that has evolved from an "open sewer" to a public amenity in less than a century. Effective management of the Chicago River relies heavily on the amount of water diverted

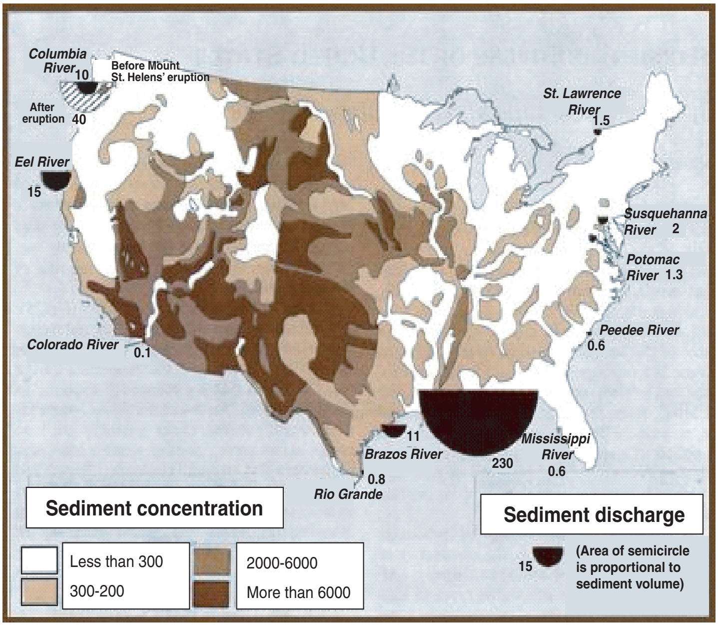


FIGURE 4-2 Map of suspended sediment concentrations in selected river basins within the continental United States and estimated sediment discharges for some of the country's major rivers. SOURCE: Meade and Parker (1985).

from Lake Michigan. Accurately measuring such discretionary flow is a challenge due to the presence of density currents laden with suspended sediment, which result in bidirectional flow during certain times of the year (Garcia et al., 2006). This is also a matter of national interest, in particular for the Great Lakes region, because a consent decree by the U.S. Supreme Court dictates how much water can be diverted by Illinois and other states bordering the Great Lakes and Canada.

Further, to maintain natural processes in altered river systems, periodic morphologically significant flows are required, but the timing, magnitude, and duration of these flows are not well understood. Many river restoration projects require specification of a dominant water discharge, or a series of flows that perform important ecological or geomorphologic functions. For example, when restoring habitat for a salmon fishery, managers need to be able to accurately estimate the timing, magnitude, and duration of the flow needed to rid spawning grounds of fine-grained sediments downstream of dams. The recent man-made flood in the Colorado River, created to revitalize the river system after years of suffering from sediment starvation, is another good example of why a better understanding of the coupling between fluid mechanics and sediment transport is needed if large dams are to be operated to promote channel and habitat restoration. Re-meandering of streams that were once channelized also requires knowledge about channel plan form stability that can only come through sound hydraulic and morphologic analyses (Abad and Garcia, 2005). Overall, these examples illustrate the clear need for the USGS to develop a program on riverine sediment transport and morphodynamics that uses state-of-the-art sediment technology, which will improve our ability to address these problems and better manage ecosystems.

The movement of sediments is also of interest to the nation because of the pollutant potential of washload and chemicals (either fertilizer or industrial waste) that attach to fine particles. Silt is often considered the number one stream and river pollutant, particularly in the Midwest. Preventing the pollution of streams, bays, and estuaries by fine-grained sediment is one of the biggest challenges facing sedimentation engineers. For example, the issue of hypoxia in the Gulf of Mexico is controlled largely by the washload made up of fine sediments from agricultural land in the heartland of America. Additionally, after years of industrial growth, there are numerous water bodies with contaminated bed and floodplain sediments, making it necessary to determine the risk of contaminated sediment resuspension so appropriate measures can be taken to manage these contaminated areas.

Why Should the USGS Be Involved in This River Science Issue?

This research could involve all of the major USGS disciplines: hydrologists (Water Resources Discipline), geomorphologists (Geologic and Water Resources Disciplines), ecologists (Biological and Water Resources Discipline), and satellite imagery and GIS (Geographic Discipline). The USGS is also positioned to partner with existing groups (e.g., support National Sediment Monitoring Program and Hydroacoustics Program) to synthesize and integrate the sediment transport work of federal and state agencies with sediment-related programs and provide comprehensive analysis to support national applications. While other agencies (U.S. Army Corps of Engineers and U.S. Bureau of Reclamation, Fish and Wildlife Service, Natural Resources Conservation Service, Agriculture Research Service, and EPA) are involved in sediment research, the USGS is uniquely positioned to serve as the synthesizer of this activity.

Additionally, the USGS has historical roots in such work (i.e., Gilbert, 1914, 1917) and is currently involved in sediment research in various rivers in Kansas, the lower Virgin River of Arizona and Nevada, and the Little Colorado River, as well as combined laboratory and field research.

What Is a Compelling Problem Related to the Recommendation?

As indicated, in the United States, sediment management is a multibillion-dollar issue, and the environmental impacts and financial losses associated with accelerated surface erosion are a growing problem (Osterkamp et al., 2004), as are concerns about the effects of sedimentation in rivers and reservoirs (Stallard, 1998; Syvitski, 2002). Additionally, limitation in sediment supply also degrades river deltas, making coastal areas more vulnerable to flooding and ocean inundation. In most regions of the United States, the landscape has been extensively modified by changes in land cover and land use associated with population growth. The specific effects of land-cover change are, however, highly variable and existing methods for predicting soil erosion and sediment yield under different land uses are not much more advanced than they were 50 years ago.

Material fluxes generated from surface erosion are uneven in both space and time. Therefore, it is important to evaluate the processes of mobilization and storage across a range of terrain types, under existing conditions and for projected changes in land cover and climate. To do this, better tools and methods need to be developed to evaluate spatial and temporal discontinuities in streamflow and sediment transport at a range of scales. This information is essential for evaluating land-based water fluxes, as well as sediment and carbon fluxes to the ocean.

A more specific and compelling problem relates to the Illinois River as mentioned earlier. The Illinois Waterway with its system of locks and dams links Chicago and the Great Lakes to the Mississippi River and thereby to the Gulf of Mexico. This linkage has significant transportation and commercial values for the state and the nation. In addition, with its numerous backwater lakes, wetlands, and floodplain forests, the Illinois River valley provides a significant habitat for fisheries, waterfowl, and other birds, and animals, making it an important ecological resource. Adaptive management of the Illinois River and many other important waterways in the nation hinges upon the development of a strong sediment monitoring program with the USGS playing a leading role and in collaboration with other federal agencies (U.S. Army Corps of Engineers, EPA, Fish and Wildlife Service).

What Are Some Examples on How the USGS Might Do This?

The potential exists within the USGS to play a lead role in developing an integrated database to monitor (and potentially model) regional patterns of erosion and sediment yield, both as natural processes and responses to disturbance. As an example of what this might look like, Figure 4-2 shows a map of suspended sediment concentrations in selected river basins within the continental United States and estimates of sediment discharges of some of the nation's major rivers. The patterns of higher and lower sediment concentration are broadly con-

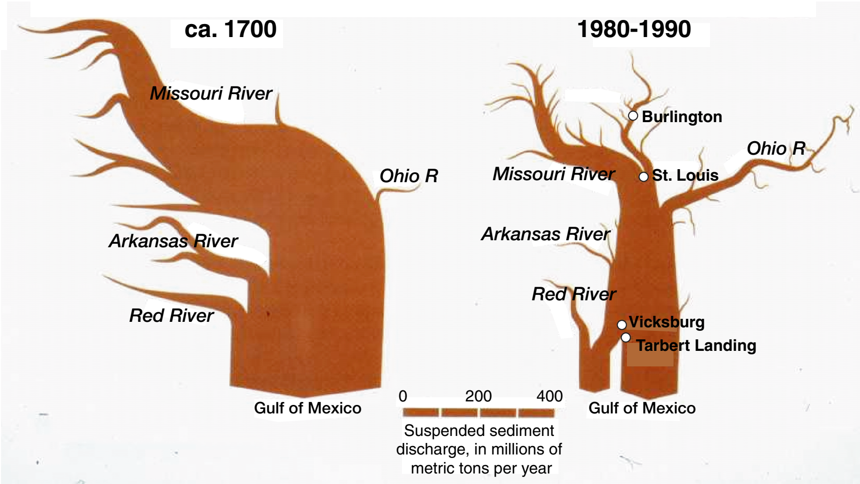


FIGURE 4-3 An estimate of suspended-sediment discharge in the Mississippi River basin. The amount of sediment entering the Gulf of Mexico has decreased significantly, leading to coastal erosion. SOURCE: Meade (1995).

sistent with regional variations in climate, rock types, and vegetative cover. Rivers draining the Great Plains and the Colorado Plateau tend to have high suspended sediment concentrations, as do some rivers in California, Oregon, and Washington. The particular combinations of precipitation, land cover, rock type, and topography in these regions combine to produce relatively high rates of erosion. Rivers draining the more humid regions of the country, including the upper Midwest and the East Coast, tend to have much lower sediment suspended concentrations. Further investigations and validations into the factors controlling erosion and sediment transport would give a clearer understanding of regional sensitivities and how regions will likely respond to future change.

In addition to spatial variations in sedimentation across the nation, sedimentation rates also change with time. Figure 4-3 shows a temporal perspective of sediment transport in the Mississippi River basin. Most notable is that the overall sedimentation into the Gulf of Mexico has decreased, leading to coastal erosion. However, where sediment yields increased or decreased depends on the location. In the 1980s, dams captured most of the sediment from the erodible Missouri River subbasin, whereas sedimentation in the Ohio River subbasin increased. Therefore, understanding sedimentation requires a better *understanding of the impacts both of erosion and dams*.

With the help of remote sensing techniques, flow and sediment transport during floods can be studied in a quantitative way. Acoustic Current Doppler Profilers (ACDP), coupled with global positioning systems and depth sounders, can provide detailed pictures of the flow structure in rivers. The phenomenon of density currents (stratified flows) in the Chicago River was discovered thanks to the ACDP measurements taken by the USGS to assess diversion flows from Lake Michigan (Garcia et al., 2006). Similar technologies are emerging to measure concentrations and sizes of suspended sediments (Szupiany et al., 2006). Swath mapping with acoustic sensors provides exceptionally detailed three-dimensional pictures of riverbed morphology, making it possible to distinguish even the smallest of bed forms (Parker and Garcia, 2006).

Sediment transport technology needs to be advanced by the USGS in partnership with other federal agencies and universities to assess sediment fluxes in rivers, deltas, and estuaries (http://water.usgs.gov/osw/techniques/sedtech21/). These advances could be focused around:

- determining the risk of contaminated sediment resuspension;
- the designing and maintaining of flood-control channels, including wetlands;
- predicting the behavior of channels that convey sediment mixtures;
- understanding sedimentation and hydraulic roughness in mountain channels;
- preventing the pollution of gravel spawning grounds by fine sediment;
- quantifying bidirectional flows in density-stratified rivers;
- restoring and re-meandering previously channelized streams;
- assessing the impact of dam removal on river sedimentation and habitat;
- developing a technique for prescribing flushing flows for removing sand and silt from gravel-bed streams;
- understanding erosion in streambanks (particularly for cohesive materials) and throughout the watershed by surface runoff; and
- improving sedimentation management in lakes and reservoirs.

Groundwater Surface-Water Interactions

Recommendation: The USGS should expand its current river monitoring and river study programs so they fully integrate the floodplain, channel, and groundwater, and the exchange of water between these systems (hyporheic exchange). The exchange of water between groundwater and rivers needs examination and quantification at multiple scales in a range of different hydrologic and geologic settings, as this process is a key component influencing river discharge and water quality, geomorphic evolution, riparian zone character and composition, and ecosystem foundation, maintenance, and restoration.

The USGS has about 7400 active stream gages, and operates hundreds of monitoring wells around the country. However, a comparatively small number of integrated studies provide only a modest database and limited understanding of the factors controlling the exchange process. Most investigations have focused on large-scale effects of water supply developments adjacent to rivers or on physical and geochemical processes occurring during exchanges in streams with small discharges (first-order mountain watersheds).

Why Is the Recommendation in the National Interest?

There are two pressing reasons why groundwater-river exchange locations, rates, and timing should be evaluated. First, these processes are being interrupted when groundwater that normally discharges to streams (see Figure 4-4) is being captured prior to reaching the river. This commonly occurs in locations where rivers are the unconfined aquifer discharge area and where groundwater use consumes or exports water from the groundwater system. Also stage modifications in regulated river systems have altered stream groundwater exchange processes, an issue that is difficult to evaluate because preregulation data are often missing. Additionally, urbanization of river systems that requires channel modi-

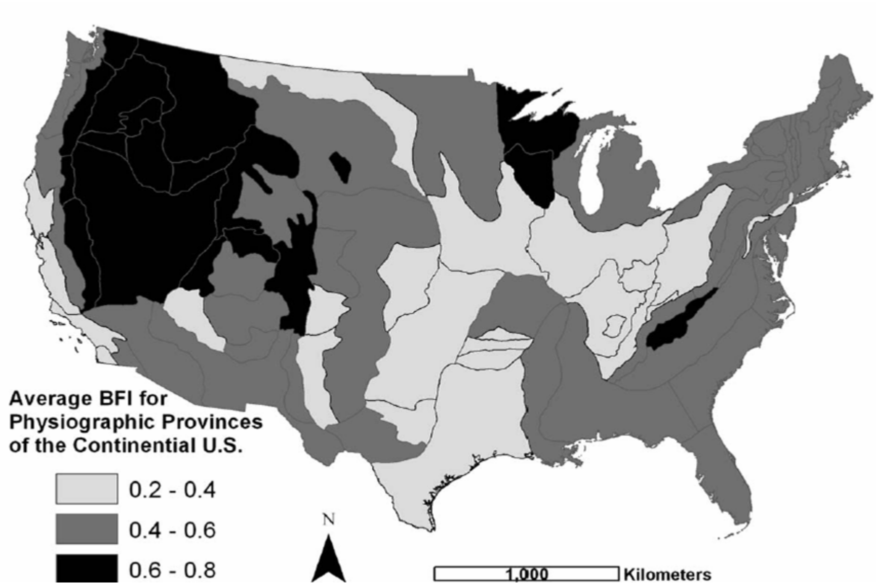


FIGURE 4-4 Average base flow fraction of streamflow attributed to groundwater. Map modified, with permission, from Becker (2006). © 2006 by Blackwell Publishing. Original map created from USGS data (Wolock, 2003) and physiographic sections of the continental United States (Fenneman and Johnson, 1946).

fications and alters the floodplain and riparian character impacts water exchange. The effects are, however, poorly characterized.

As the demand for water grows, groundwater extraction from river floodplain aquifers is commonly used as a source of additional potable water. Yet, the impacts of such operations on all aspects of river functions are poorly known. One observed effect is the alteration of stream hydrographs (e.g., the Ogallala Aquifer; Sophocleous, 1998). Therefore, a national effort is needed to characterize both the spatial, temporal, and magnitude of this exchange process in varied river and hydrogeologic settings, and the impact water use and management have on the exchange process in a river system.

Hyporheic exchange processes also underpin other stream and riparian functions including sediment transport and deposition, water and quality, and water temperature, which all relate to the quality of the ecological habitat. Such hyporheic issues are not just limited to the dry western states like they once were. With population growth in the eastern United States, the demand on shallow, river-connected groundwater systems to supply water has increased.

Second, to regain natural hydrologic, geomorphic, and ecologic functions, the nation has begun to restore thousands of kilometers of modified river systems. Yet little is known about how the groundwater-river exchange processes influence riverine natural, altered, and restored conditions. For example, there is a national need to determine how rivers function as water treatment systems as they process and cycle nutrients, carbon, and other elements in the channel and floodplain systems, and how water exchange supports ecological systems. They do this partly by exchanging river water with the river bed and bar water, and the adjacent floodplain groundwater system. Though it is recognized that hydrologically generated disturbance to river riparian systems (e.g., Resh et al., 1988; Junk et al., 1989; Poff et al., 1997; Schlosser, 1987; Townsend, 1989; Poff and Ward, 1990; and Townsend and Hildrew, 1994) and extreme events like floods and droughts reset fluvial ecosystems, the influence of groundwater and river exchange locations and rates on these disturbances is poorly understood (Poff et al., 1997; Gasith and Resh, 1999; Bunn and Arthington, 2002).

Why Should the USGS Be Involved in This River Science Issue?

The USGS is the national leader and has a long history of conducting unbiased studies of the nation's aquifers and rivers (e.g., Regional Aquifer Systems Analysis, Groundwater Atlas, the National Stream Quality Accounting Network [NASQAN], and NAWQA). It is also a leader in developing many, now standard, hydrologic methods and tools used to characterize groundwater and surface-water interactions (Rorabough, 1963; Stallman, 1963; Lapham, 1989; Constantz and Thomas, 1996; Constantz, 1998; Constantz et al., 2003; Stonestrom and Constantz, 2003).

The extensive USGS streamgaging network combined with the large number of regional and special project synoptic survey datasets housed at the state and regional centers provides a wealth of data. With these datasets and existing networks, the USGS seems the logical place to focus resources to investigate the stream-groundwater exchange process at a national scale.

The lake program of the USGS, with some modification, provides a template for the development of aggressive data mining efforts and the approaches for determining the location and timing of new field instrumentation to understand exchange rates. Therefore, the expertise needed to design and initiate hyporheic and riparian zone hydrology and ecosystems research is already present in the research conducted at regional USGS offices. Existing research efforts in groundwater-stream interaction include investigations to quantify denitrification and related processes in an agricultural watershed of the Mississippi River basin (Böhlke et al., 2004).

What Is a Compelling Problem Related to the Recommendation?

The capacity of river systems to affect water quality by processing pollutants such as nutrients has enormous application to a nationwide problem of the unsuitability of large numbers of waterbodies for their designated uses. The Clean Water Act is a major driver for research in this area, through requiring estimates of total maximum daily loads (TMDLs) of dissolved and suspended material in rivers. Thousands of water bodies throughout the country, and a vast area of the Gulf of Mexico, receive excess N and P, and much of the supply comes from nonpoint sources, notably agriculture. Although construction of forested riparian buffer zones and other initiatives are important to solving this problem, an in-depth understanding of how nutrients cycle between rivers, groundwater, and sediment is critical to developing long-term solutions and the most effective mitigation strategies.

What Are Some Examples on How the USGS Might Do This?

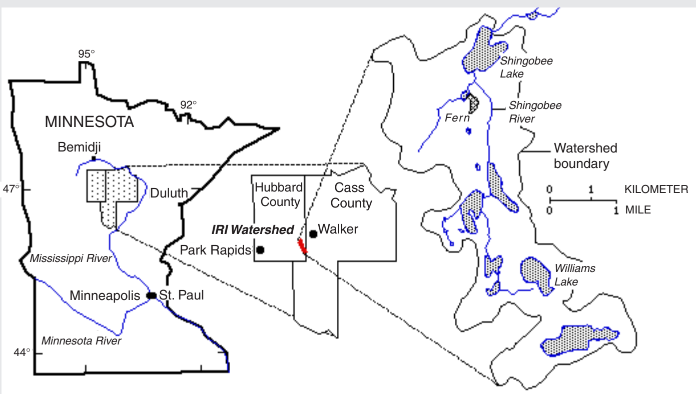
Future synthesizing and expanding upon current and past studies involving groundwater and surface water are natural extensions of what the USGS already does. Such future work, if coupled to the strengths of the Biological and Geographic Disciplines and partnered with other agencies, offers an unprecedented opportunity to learn how groundwater and surface-water interaction affects riverine and riparian environments and biota across the spectrum of different hydrologic and climatic regions of the United States. Groundwater and surface-water interaction can be studied within current National Research Program initiatives (water.usgs.gov/nrp/) and incorporated as part of ongoing national initiatives, such as NAWQA. The most long-standing of these projects is outlined in Box 4-2.

Long-term hydrologic data from USGS streamgages would be the starting

BOX 4-2
Shingobee Headwaters Aquatic Ecosystems Project

The USGS program studying the role of lakes in the hydrologic system incorporates close cooperation between the National Research Program (NRP) and Water Science Center offices and is an example of how interdisciplinary science in rivers could be done. The Lakes Research Program of the USGS has been active for more than 25 years, beginning in the late 1970s with the study of Williams Lake in northern Minnesota (see figure below). At that time the Minnesota Division of Waters provided funds to the Minnesota District Office to collaborate with Tom Winter, director of the Lake Research Program, in his field studies and interpretation. This collaborative approach ultimately embraced scientists from other divisions of the USGS, numerous universities, state agencies, other federal agencies such as NASA and NSF, and the International Atomic Energy Agency. The overall effort is now well known as the Shingobee Headwaters Aquatic Ecosystems Project (SHAEP). The purpose of SHAEP is to develop interdisciplinary tools and information on how atmospheric water, surface water, and groundwater function as an integrated system. Participating scientists provide their own funding, and there are no constraints on the number of scientists participating, their discipline, or on duplication of effort.

Involved scientists from both within and outside the USGS cover the gamut of multidisciplinary fields from the physical, geochemical, and biological sciences. The research results of SHAEP have led to major interdisciplinary understanding of lake systems, including their biology, geochemistry, and hydrology (http://wwwbrr.cr.usgs.gov/projects/SHAEP/index.html). This program is an outstanding example of how multiple parties and organizational branches of the USGS have worked in concert to achieve a scientific organization model where the sum of the parts is actually greater than the whole. The larger NRP lake program includes studies of lakes throughout the United States, with long-term sites equivalent in length and scope located in New Hampshire, North Dakota, and Nebraska. These studies are all being done in an interdisciplinary way incorporating district, university, and state and federal agency scientists collaborating with the NRP.



Location of the USGS Shingobee Headwaters Aquatic Ecosystems Project (SHAEP). SOURCE: http://wwwbrr.cr.usgs.gov/projects/IRI/WSPintro1.html.

point for such characterization, particularly in the context of comparative studies among streams reaches within different climatic and geomorphic settings. As indicated in the NRC report on the National Streamflow Information Program (NRC, 2004d), the USGS gage network has been critical to providing the fundamental data supporting the emerging field of hydroecology in the last decade. For example, regional flow regime classifications have been constructed using streamflow data from the USGS National Streamflow Information Program. These kinds of studies could ultimately lead to a groundwater-stream exchange classification that could be used to evaluate stream functions and possibly provide a focus for stream restoration efforts.

One example of how large-scale evaluations of riparian and hyporheic zones might be done is by calculating the extent to which groundwater delivers nutrients to streams by conducting focused monitoring in the hyporheic zone at type-reaches across either hydrogeomorphic regions or gradients of human landscape alterations. These monitoring efforts could then be coupled to modeling approaches. This would allow for the evaluation of how the hyporheic zone transforms nutrients at multiple scales of stream order by using a series of field experiments as part of an interagency partnership (i.e., with EPA).

As might be expected, there are many approaches that can be used to tackle groundwater and surface-water interaction within streams and the riparian zone in a manner that leads to transfer across the spectrum of riverine environments. Because of uncertainties associated with estimates of hyporheic exchange based on any single technique, different techniques should be developed to conceptually understand hyporheic processes at different spatial and temporal scales. For example, remote sensing may be useful in identifying spatial and temporal variations in groundwater discharge in streams over time based on temperature or soil moisture content proximate to streams (using multiple images). Different remote sensing techniques to characterize riparian zone hydrology likely would have to be investigated for different regions (i.e., arid versus humid regions).

CONCLUSIONS

Clearly, the USGS is positioned to provide national leadership in a river science initiative for the nation. From the organizational strengths of the USGS, which incorporate the broad spectrum of science and technology needed to study rivers, coupled to its unique nonregulatory or commercial science and information mission, the USGS can play a vital role in addressing problems related to the pervasive changes occurring to our nation's rivers. Through collaborations with state and local governments, as well as other federal agencies, the USGS is also well suited, perhaps ideally suited, to broker interdisciplinary teams and efforts to do the broad-scale and novel new river science initiatives needed to advance river science for the public good.

Of the many river science questions, the committee has identified five science priority areas where the USGS should take a leadership role.

1. Through its cartographic capabilities, the USGS has provided the leadership for mapping the nation's watersheds. Combining this strength with its expertise in the areas of river hydrology, geomorphology, and ecology the USGS should embark on efforts to survey and map multidisciplinary characteristics of our nation's rivers, providing a geographical baseline that supports an integrative river science.

2. Through its scientific research capabilities, the USGS has developed an essential suite of mathematical and other tools that can be applied to a broad range of river science questions. Building on these accomplishments, the USGS should develop process-based models that simulate the interactions between physical-biological processes, providing the nation with an ability to predict ecological change in river systems to support science and river management.

3. With its multidisciplinary expertise in areas of river science, the USGS should conduct research that provides a scientific-basis for characterizing environmental flows needed to support the ecological structure and function of river ecosystems, and in partnership with other agencies' activities, evaluate the effectiveness of restoration efforts designed to improve river ecosystem health.

4. Historically, the USGS has been a leader in monitoring river sediment transport and studying the interactions between hydrology and fluvial geomorphology. The USGS should strengthen its research efforts in sediment transport and geomorphology on our nation's rivers to address the increasing problems due to alterations in river flows and channel morphology.

5. Major gaps remain in our scientific understanding of the exchange of water between a river and connected groundwater systems. The USGS should focus investigations on groundwater and surface-water interactions in rivers at a range of scales, providing information on how the character and composition of these waters affects river water quality and ecosystem characteristics.

Although the USGS is poised to provide national leadership in these river science priority areas, these activities must be supported by effective data collection and management and an institutional structure that allows for an agencywide multidisciplinary research initiative. In Chapters 5 and 6, we address the river monitoring, data management, and institutional components that should underpin the USGS's contribution to river science.

5

Monitoring and Data Management for USGS River Science

The USGS and other agencies maintain the river monitoring and data management infrastructure that supports existing activities in river science and management. However, this infrastructure is woefully inadequate to address the immense and growing problems related to the deterioration of the nation's rivers. The lack of sufficient data for river systems is one of the biggest obstacles to providing the science-based information needed to effectively manage the nation's rivers.

Although Chapter 4 identifies five science priority areas where the USGS can contribute to a national effort on river science, how the USGS is able to address these priorities is predicated on new river monitoring and data management efforts that fill science data gaps in critical and neglected areas. Chapter 5 describes activities that must build on multidisciplinary databases created from national monitoring networks and intensive local sampling, as well as other ancillary geophysical datasets, for (1) a survey and synthesis of river features and (2) the development of models of river processes. For science priorities in focused topic areas, Chapter 5 identifies data gaps in (1) ecological monitoring baselines for adaptive management and the establishment of environmental flows, (2) water and sediment flux monitoring for understanding changes in sediment transport and river geomorphology in response to dam operations, land-use changes or river restoration activities, and (3) monitoring the exchange of water and chemicals between groundwater sources and rivers and their effects on characteristics of floodplain and riparian areas. Therefore, new USGS initiatives to enhance and strengthen data collection, archiving, and dissemination are an essential element of a USGS river science initiative.

Expanded river monitoring and data collection activities at the USGS also need to provide fundamental long-term baseline monitoring in anticipation of the nation's need for river science information. Although monitoring is usually designed to address specific problems, the value of a consistent national baseline monitoring approach to address emerging problems is frequently overlooked and undervalued. Understanding the impacts of agricultural and urban land-use changes on rivers and the influence of climatic variations on biogeochemical and water cycles are just two examples of the unforeseen usages of long-term streamflow observations from USGS streamgages. Another example is the integrated study of hypoxia in the Gulf of Mexico (Goolsby et al., 1999), which has been instrumental in promoting a scientific understanding of the sources and fluxes of nutrients responsible for this problem. The report builds on baseline streamflow and nutrient monitoring by the USGS. Unfortunately, the degradation of the nation's baseline monitoring of rivers over time (NRC, 2004d) threatens our ability to assess emerging problems in river science.

In the first part of this chapter, we describe opportunities for the USGS to build on its data collection infrastructure and expand its monitoring of hydrologic, geomorphic, chemical, biological, and ecological processes in river and floodplain ecosystems for national and regional science synthesis. We focus on enhancements in streamflow, biological, and sediment monitoring and on the establishment of a reach-scale monitoring approach. This section also describes some considerations for the general design principles of a modern river monitoring system, highlighting the importance of partnering monitoring efforts with other organizations and incorporating measurement technologies.

The value of these enhancements to river monitoring activities to river science depends on easy access to data, and the ability to efficiently utilize diverse measurements and data products from multiple disciplines, by the community of scientists and decision makers. In the second part of this chapter we discuss the data management challenges for river science, and recommend an informatics component for integrated data archiving, dissemination, and management.

One of the fundamental implementation challenges for a nationally relevant river science program is to leverage data resources to avoid duplication and target data collection activities to support the portfolio of data needs and uses. Although the focus of this chapter is on USGS activities in monitoring and data management for river science, coordination and cooperation among the federal resource management agencies and their nonfederal partners is imperative because of the scope, scale, and intensity of data needed to support river science. Plans for interagency collaboration need to be an integral part of any USGS river science monitoring and data archiving activity. No single federal agency can collect, quality assure, manage, and disseminate all data and observations relevant for river science. Yet all federal agencies, nonfederal partners, and stakeholders with an interest in river science and resource management will benefit from access and availability of accurate, reliable, and well-documented data.

INTEGRATED DATA COLLECTION AND RIVER MONITORING

Scientific data related to riverine systems, and the knowledge generated using these data, are needed to support decision making for many of today's policy and management challenges related to rivers (see Chapter 2). Whether the problem is to establish policies to prevent river degradation from upstream urban land-use changes, to prioritize investments in river restoration, or to decide whether to remove a dam, scientific data informs the decision-making process. But, there are critical gaps in river monitoring. Making river policy and management decisions with limited or insufficient data leads to costly and potentially irreversible mistakes. Additionally, in some cases, the absence of data fuels controversy, delaying or preventing policy makers from making decisions. Where decisions are made but their impacts on rivers not closely monitored, science and the public never learn the valuable lessons from successes and failures that would improve future policy and management decisions.

Monitoring of our nation's rivers is the foundation for the USGS's contribution to river science. By expanding monitoring activities on rivers, the USGS can develop a modern, coordinated 21st-century river monitoring system. The USGS streamgaging network, with its quality-controlled and publicly accessible data archive, is the fundamental building block for such a system. Still, a river monitoring system to support integrative river science and river management must encompass not only streamgaging but also the chemical, biological, and sedimentological characterization of river flows. It would merge other components, such as a national sediment monitoring program and biological reach indicators, as integral elements of a coordinated system. It would include the mapping of the physical and ecological conditions of rivers and riparian areas. Finally, it would establish protocols for data collection and dissemination, and investigate new river monitoring technologies.

Recommendation: The USGS should expand its monitoring activities on rivers to better incorporate river physical, chemical, and biological conditions within its existing river and streamflow monitoring programs. Its goals should include development of a 21st-century river monitoring system for data collection, transmission, and dissemination.

Data Collection Needs for River Science

Data gaps exist in all priority research areas in river science (see Chapter 4). Monitoring baseline conditions is essential to establish environmental flows that support ecological functions. Synthesizing baseline information provides guidance for river restoration and adaptive management for degraded rivers, while scientifically designed monitoring of the outcomes of these activities is needed to test the underlying hypotheses guiding decision making. These baselines also help in understanding riparian areas that are also affected by changes in flow, sediment, and nutrient compositions; developing a predictive understanding of riparian ecosystems requires data on the physical system, the vegetation, and the interactions of surface and groundwater in riparian corridors.

Relatively speaking, streamflow data are generally available for larger river systems, but coincident observations of water quality, sediment transport, biological indicators, and riparian ecosystems, are usually lacking. For smaller river systems, there are few integrated river datasets. Therefore, continuously monitoring key observations that address these issues for extended periods in larger streams is, at a minimum, a prerequisite for synthesizing this information to generate estimates at smaller unmonitored sites.

For integrative scientific investigation of river and riverine processes, the biggest challenge in data collection is planning and implementing a cost-effective, yet scientifically sound, mix of hydrologic, geomorphic, chemical, biological, and ecological monitoring. For example, addressing certain science questions in river restoration may well require data on river and riparian ecology, hydrologic conditions, sediment concentrations and fluxes, watershed conditions, and economic variables (Box 5-1 and Appendix B). To be effective, integrated monitoring networks need to be designed based on scientific principles, utilize documented data protocols, and produce quality-assured/quality-controlled (QA/QC) datasets.

Such measurements often cannot be done at a single site. The relevant physical processes often act at different characteristic scales. For river geomorphology, some characteristic scales of length include the channel width, which responds to flow and sediment transport regimes; the meander wavelength, which is related to geologic and geomorphic processes within the river valley; and the river network link length, which is related to landscape evolution and river network development processes. Pool spacing, which has important influences on stream habitat, is related to the width of rivers, meander wavelengths, and the length of stream segments between junctions relative to drainage density and average hillslope length (Leopold et al., 1964; Gregory and Walling, 1973; Rodriguez-Iturbe and Rinaldo, 1997).

The connection between processes and characteristic river scales is also evident in the River Continuum Concept (Vannote et al., 1980), which relates stream size and river order to the structural and functional attributes of river biology. Matching the spatial and temporal scales of physical measurements with the interactions between hydrologic, chemical, biological, and ecological processes is a significant challenge. Still, meeting this challenge is necessary to understand the complex interactions, and to develop predictive models that couple them.

BOX 5-1
Valuable Data Resources for Answering River Restoration Science Questions

Representative Research Questions

How can modifying hydrology and geomorphology restore riverine ecology?

How can the ecological success of restoration be assessed?

What might be the cumulative impacts on restoration of multiple segments of rivers?

What are hydrologic or chemical ecosystem thresholds at multiple scales?

Riparian and River Ecological Data

Baseline ecological data
Index conditions
Macroinvertebrate/coastal invertebrate
Algal distribution identification
Species survey
Indicator species
Behavioral patterns
Micromet (fluxes and isotopes)
Sap flow

Hydrologic Data

Groundwater data
Hyporheic data
Hydrologic connectivity
Surface flow velocity distribution
Surface-water flow/timing
Chemical composition of waters
Age dating and natural tracers
Precipitation and meteorological data

Sediment Data

Sediment load
Sediment deposition/erosion pattern
Sediment size distribution
Sediment quality
River/banks surveys

Watershed Physical Data

Soils types and quality
Wetland survey
Land-use data
Historical data
Remote sensing

Economic Data

Economic valuation

See Appendix B for a more comprehensive set of research questions and the types of data required to address them.

The USGS Role in Monitoring for River Science

The USGS has a federal mandate to serve the nation by providing reliable scientific data and information. Its monitoring activities are distinguished for their scientific rigor and quality control. The USGS has also been a leader in data distribution and in the development of instrumentation for river monitoring.

The core river monitoring capabilities of the USGS already serve as our nation's primary data resource in many areas of river science. The most visible example is the streamgaging network (see Chapter 3), with over 7000 active sites. At selected sites, the USGS also continuously records water quality (including pH, specific conductance, temperature, and dissolved oxygen) and suspended sediment concentrations. These data are archived and disseminated online through the National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis/). Through satellite telemetry systems, NWIS provides real-time access to streamflow data at most sites, and water-quality data at some.

USGS expertise in data collection and river monitoring is incorporated in the design and implementation of its research programs. For example, the National Water-Quality Assessment (NAWQA) Program (see Chapter 3) has an experimental design that schedules intensive sampling periods to monitor trends in water quality and to help identify the reasons for these trends. The USGS uses standard data collection protocols to provide a nationally consistent water-quality dataset. One example of a current program-specific monitoring effort is the Long Term Resource Monitoring Program (LTRMP) for the upper Mississippi River (see Chapter 3). In this program, the USGS samples fish, macroinvertebrates, vegetation, and water quality from six field stations, and combines these data with other data (e.g., bathymetry, fish passage information at locks and dams, water levels, and discharge), to provide information to assess the impacts of river management decisions on biological resources, and to support development of future alternatives.

Still, the USGS must build on its existing capabilities to more comprehensively enhance its river monitoring to address the nation's need for science information on rivers. In the following subsections, we describe recommended enhancements in river monitoring for a USGS river science initiative, and describe some considerations for the design of a modern river monitoring system.

Enhancements in Streamflow Monitoring

Recommendation: The USGS should investigate cost-effective opportunities to augment site information and, in some cases, increase the sampling at targeted National Streamflow Information Program streamgages to make the gage data more useful for river science initiatives. There should be a renewed effort to collect, archive, and disseminate opportunistic data for hydrologic extremes (floods and droughts).

The USGS streamgaging network is one of the most important resources available for river science and management. The National Streamflow Information Program (NSIP) needs to be fully implemented and maintained for long-term archival data to assess trends driven by anthropogenic landscape changes and future climate change. There are some efforts that the USGS can take within this infrastructure of data acquisition that would require only modest additional resources but would maximize the usefulness of NSIP streamgages for river science. These were highlighted in the NRC report on NSIP (NRC, 2004d), but they deserve to be summarized here.

First, the USGS needs to archive and disseminate previously and recently collected cross-section and unit value (hydrograph) data along with the streamflow data, which are readily accessible as daily averages and flood peaks. Both fine resolution streamflow time series and cross-section data are essential to document channel changes, evaluate nonstationary hydrograph characteristics, assess the duration and frequency of floodplain inundation, and infer hydro-ecological relationships. Rescuing cross section and unit value data at both carefully selected index gages and at gages where the cumulative impacts of natural and anthropogenic changes can be critically analyzed would fill crucial data gaps.

The USGS should investigate cost-effective opportunities to augment site information and, in some cases, increase the sampling at targeted NSIP streamgages to make the gage data more useful for river science initiatives. For example, expanding the monitoring of river temperature and water quality (including pathogens and organics) at some NSIP sites would be invaluable with respect to regional and national synthesis. The USGS might also consider developing a plan to collect stream gradient and bed material size at more gaging station locations, perhaps in conjunction with other organizations.

Finally, there should be a renewed effort to collect, archive, and disseminate opportunistic data for hydrologic extremes (floods and droughts). The series of 12 reports after the 1993 upper Mississippi River flood (e.g., Parrett et al., 1993) serves as a prototype to emulate; it demonstrates how opportunistic sampling and timely dissemination of unbiased information can contribute to the scientific and public debate that follows such events. Similar efforts over the course of widespread severe droughts are needed to study their effects on river ecology. For making opportunistic measurements, the USGS should consider the role of new measurement technologies for expanding the gaging network (e.g., to collect additional crest-stage and slope-area data), as noted in NRC (2004d) and alluded to in the "Measurement Technologies" section below.

Sentinel watersheds could serve as stream morphology and sediment reference sites across fundamental landscape divisions. Still, a key question is whether the stretches of rivers where the sentinel streamgages are now located are representative of the watershed and ecoregion of which they are a part. Typically, streamgages are sited on stretches best suited for flow measurement (e.g., access and clear channel geometry). Using an integrative approach, the siting of sentinel streamgages should be reevaluated to best measure stream processes.

Enhancements in Biological Monitoring

Recommendation: Expanding the collection of biological and ecological data at streamgaging sites is needed to develop integrated biophysical datasets for river science. However, fundamental questions remain on how to implement a monitoring program to support national and regional synthesis. The USGS should continue its efforts to define relevant biological monitoring activities for national implementation, while still expanding biological and ecological monitoring in a targeted fashion to address clearly defined regional data needs.

NSIP provides a strong framework for assessing river hydrology and integrating flow with other measured variables for river regime characterization. However, there are no comparable biological data routinely collected at NSIP gages to characterize the ecological or biological status of our nation's rivers on the whole. Instead, biological data are collected as part of programs like NAWQA and LTRMP, with sampling designed to track regionally significant biological and ecological indicators.

A key question is whether there are river biological and ecological indicators that need to be surveyed nationwide, or whether most indicators are meaningful only in a regional or local context. There is a clear need to identify such indicators to assess ecological trends in river systems; many agencies and research organizations have research programs designed to develop ecological indicators for both scientific and management applications. For instance, the EPA's newly completed Wadeable Streams Assessment, which was a snapshot of the ecological condition of small streams throughout the United States using 500 randomly selected sites, used benthic macroinvertebrates as biological indicators, phosphorus, nitrogen, salinity, and acidity as chemical indicators, and streambed sediments, instream fish habitat, riparian vegetative cover, and riparian disturbance as physical condition indicators (http://www.epa.gov/owow/streamsurvey/).

Developing ecological indicators to track changes in rivers and provide early warning on river impairment is a significant component of the EPA's Environmental Monitoring and Assessment Program (EMAP) as well. At the USGS, the Biological Resources Discipline is wrestling with the question of national indicator monitoring needs as part of its Status and Trends Program (see Chapter 3). These activities, within and external to the USGS, may well lead to a future consensus on a national approach to the monitoring of indicators.

In the meantime, the USGS should continue its support of initiatives such as the National Biological Information Infrastructure (NBII), and similar biological data gathering in cooperation with state and other federal agencies, as monitoring data assembled by NBII are valuable for a national synthesis of biologic status and trends (USGS, 1998). The USGS National Water-Use Information Program (NWUIP) is an analogy for an initiative that uses multiple sets of data of mixed quality. NWUIP involves multiple partnerships with state agencies, from which water use data of highly variable quality is synthesized at the national level (NRC, 2002b). In particular, NWUIP leverages its district structure to facilitate the sharing of data from state and local water agencies.

On a regional basis, the LTRMP is a prototype for doing science-quality monitoring to meet an experiment design that incorporates river biological components. A current weakness of LTRMP is its limited integration of monitoring to test distinct hypotheses and to develop models and predictive capabilities. Still, the data monitoring and exploration effort exemplified by this program should be emulated elsewhere, if done in an integrated scientific way that includes elements of hydrology, geomorphology, and water quality. Expanding biological monitoring activities in a targeted fashion, using an LTRMP prototype, is an approach that the USGS can readily implement to collect integrated biological and ecological datasets needed for research on USGS river science priorities and site-specific river management problems.

Enhancements in Sediment Monitoring

Recommendation: Leveraging the infrastructure of the streamgaging network, the USGS should greatly expand sediment monitoring of the nation's rivers. To meet the growing needs for sediment data, the USGS should be a leader in developing a comprehensive national sediment monitoring program.

The decline in sediment monitoring in recent decades from approximately 300 sites in 1980 (Glysson, 1989) coupled with the growing needs for sediment information to address an expanding number of river management issues act together to generate a major data gap in river science understanding (see also Chapter 4, "Sediment Transport and Geomorphology"). This gap is exacerbated by the economic consequences of accelerated erosion and sediment transport; sediment-related damages for North America are estimated to be on the order of $16 billion annually (Osterkamp et al., 1998).

The Subcommittee on Sedimentation (SOS) of the Advisory Committee on Water Information (ACWI) has called for a national monitoring program for sediment investigation (Osterkamp et al., 2004). The proposed program includes a core network with continuous fluvial-sediment monitoring at existing flow and water-quality gages. Other components would address improving supplementary sampling at existing sites, measurement techniques, data synthesis and assessment, and the rescuing of archives of previously collected sediment data. The SOS reported that if the program leads to a 1 percent reduction in sediment-related damages through better river management, the damage reduction would be about 40 times the program cost.

The USGS should take a lead in developing a national sediment monitoring program. Leveraging the infrastructure of the streamgaging network, the USGS should enhance the sediment monitoring at selected NSIP gages. To maximize the utility of the sites for river science, coincident measurement of temperature and other water-quality variables should be made. New measurement technologies hold promise in advancing this effort by both reducing the costs of sediment monitoring and enhancing the information gained. For instance, the use of hydroacoustics to measure three-dimensional flow structure would provide data to better interpret sediment flux measurements. Analysis of the chemical composition of river sediments would be valuable for identifying source areas for fluvial sediments.

Establishment of Reach-Scale Monitoring

Recommendation: An index reach monitoring approach would help address many data needs for USGS river science priorities. To integrate monitoring of physical, chemical, and biological conditions for river science investigations, the USGS should begin efforts to design and implement sampling plans on reach scales.

At the reach scale, the river and floodplain ecosystem is driven by its physical settings and hydrologic conditions, including the stream slope, hydrologic regime, groundwater interactions, and land use. Few monitoring networks adequately measure both the drivers and ecosystem responses to support scientific understanding and model development at the reach scale.

The USGS should consider establishing index biological reaches throughout the nation to support its science priority areas for river science (see Chapter 4). Index reaches would serve as integrated measures of reach-specific responses to changing environmental conditions and support the careful evaluation of responses of biota over time. Index biological reaches would be locations where coupled measurements of river flows, groundwater levels and fluxes, and water quality are made.

As part of a continuous monitoring effort, the USGS also needs to map riparian cover of index reaches on at least an annual or semiannual basis. Remotely sensed data, combined with in situ observations by the USGS and other agencies, could be used to develop riparian cover maps. Reach-level riparian ecological services, such as flood control, bank storage of water, interception of pollutants, and habitat diversity, can be inferred from relatively coarse-grained riparian cover information, hydrologic data, and water-quality data.

The colocation of biological and hydrologic monitoring would help assess how much water is needed to sustain ecological goods and services and help establish the environmental flows needed to meet ecosystem needs. The data collected at reaches would also help in understanding the role of groundwater exchange, the hyporheic zone, and the chemical composition of these waters, on river ecosystems. In turn, index reach monitoring could provide a means for evaluating the effects of river restoration or adaptive management experiments. The reach-scale activities described in Chapter 4 for the "Surveying and Synthesizing" science priority area would be an important first step in designing a network of index reaches that sample across diverse physical and ecological settings.

It should be noted that "reach" as a river concept has a variety of definitions and invokes very different pictures in the minds of river scientists. Within the USGS, at least three programs operate in reaches—the Grand Canyon, the Upper Mississippi (LTRMP sampling reaches), and NAWQA. However, these programs operate at different spatial and temporal scales. The USGS would need to consider which current programs are operating at an appropriate scale for this concept to determine what programs might be good to build off of.

River Monitoring—Design Principles

Recommendation: For the design and implementation of a coordinated river monitoring system, the USGS should develop specific monitoring goals and objectives for building on its existing infrastructure. The USGS should prioritize these activities based on variables with broad science and management applications.

Unlike previous NRC reports for specific USGS programs like NAWQA (NRC, 1990), NWUIP (NRC, 2002c), and NSIP (NRC, 2004d), detailed recommendations on the sampling design and implementation of a river monitoring system cannot be made for a USGS river science initiative; such an initiative encompasses much more than a single USGS program. Hence, the sampling design and implementation of its river monitoring components would depend on the scope and institutional organization of the science priority areas, involve elements from all the science disciplines of the USGS, and conceivably build upon and integrate monitoring activities of many existing programs. Still, general principles that should guide enhanced monitoring activities are worth mentioning.

As with the sampling design for NSIP and NAWQA, a USGS river monitoring system needs a sound scientific framework for implementation. For example, the USGS has outlined five components for NSIP, covering topics ranging from data collection strategies to information dissemination and measurement technologies. For its base streamgaging network, the USGS has defined specific monitoring goals, ranging from measuring flows at major river outlets for water budget accounting to monitoring sentinel watersheds to evaluate long-term trends. A similar design framework is needed to establish a meaningful USGS river monitoring system.

A modern river monitoring system would necessarily contain certain elements. There would be a core network of river monitoring sites closely coupled to the NSIP network. Selected sites within the core network would maintain intensive integrated reach-scale measurements of hydrologic, geomorphic, chemical, and biologic variables. The system would be supported by the mapping of the physical characteristics of rivers and the riparian vegetation at reach-scale monitoring sites. The design of the river monitoring network would meet specific monitoring goals, such as determining sediment transport and sediment budgets for major basins, and assessing trends in river conditions. The data collected by the river monitoring system would be quality controlled and archived using data and geospatial information standards (see the following section on "Integrated Data Archiving, Dissemination, and Management") that facilitate public access and use.

Expanding monitoring at sites within the network should be designed primarily to support USGS river science priorities for improved understanding and characterization of river processes. A long-term commitment to monitoring at selected sites is required to develop necessary biophysical data archives. The sampling must also consider the data needs for estimation of critical river conditions at unmonitored sites, as is exemplified by the USGS activities in regional interpretation of flow and water-quality data (e.g., SPARROW).

Clearly, cost constraints mean that choices have to be made on what variables to measure and where. The selection of hydrologic, geomorphic, chemical, and biological variables to monitor at sampling sites should be guided by both the river monitoring system design goals and the river science drivers within the region. By way of illustration, Appendix B provides a brief survey of pressing river science questions, and describes the data inventories that are needed to address these questions. Many of the needed datasets can be assembled from existing inventories of the USGS and other agencies. Others may be met through monitoring activities designed to support specific river management decisions (by the USGS or other agencies). Still, data gaps will remain in many situations. By identifying key river science questions on a regional basis, the USGS can target its limited resources to expand sampling at NSIP sites and index biological reaches to provide long-term monitoring of variables that address relevant river science data needs.

In some cases, it may be possible to leverage or combine monitoring efforts of existing programs (e.g., National Stream Quality Accounting Network, NAWQA, LTRMP, National Research Program) in more efficient ways. For example, the Water Quality in the Yukon River Basin Project provides an example of integrating science and monitoring programs. Data obtained from fixed site and synoptic sampling of water quality and lake sediments is being used to address the multiple scientific issues in the basin. These include (1) carbon cycling: the origin, quantity, chemical characteristics, fate and transport of carbon at specific locations along the river and at high and low flow; and (2) mercury stores and cycling: concentrations and chemical forms of mercury in water, sediment, and biota; transport phases of inorganic and methylmercury; methylation rates in sediments; and release rates of gaseous mercury. The program, still in its early stages, was initiated with funding primarily from NASQAN; other USGS contributors include the Earth Surface Dynamics, Mineral Resources, and Biomonitoring of Environmental Status and Trends Programs.

Analogous to the data collected with the streamgaging network, which are used for a range of purposes that were never conceived by the individual gage sponsors, so too can river monitoring data be used for a range of river science questions. A perusal of the river science questions and data needs in Appendix B shows that many kinds of monitoring data, including baseline ecological data, indicator species, water flow and timing, and sediment fluxes and grain size, can be heavily leveraged for many different kinds of river science questions. Whenever possible, the USGS should prioritize its expanded data collection and mapping activities on those variables with broad science and management applications.

River Monitoring—Partnering in Monitoring Efforts

Recommendation: The implementation of a USGS river monitoring system should be informed by the data and science information gaps that limit effective policy and management decision making of other organizations, including mission-oriented government agencies at federal, state, and local levels, nongovernmental organizations, and academic research institutions. Partnering with these groups to design and implement scientific data monitoring in support of site-specific management and research objectives must be a component of USGS river monitoring.

A unique challenge and opportunity for the USGS in developing a coordinated river monitoring system is that many other federal and local agencies have a diverse range of river monitoring components to support their management activities. For instance, the EMAP effort of the EPA collects physical, chemical, and biological data on rivers to assess existing conditions at monitored and unmonitored sites (e.g., the Mid-Atlantic Integrated Assessment [MAIA]). EMAP has developed a considerable body of knowledge on indicators that the USGS can profit from. EMAP's probabilistic sampling design is in stark contrast with the USGS's fixed location sampling network, but this difference in approaches can be turned into a strength as results from the programs are compared and their resulting predictions tested. Thus, the USGS river monitoring system should seek to complement, rather than duplicate or replace, monitoring efforts of other agencies.

Increasingly, river science monitoring problems will involve partnerships between the USGS and other agencies involving site-specific problems, with specific actions and expected outcomes. Clearly, USGS expertise in the design of data collection networks for experiments, and its reputation for impartiality, can contribute to such multiagency efforts by providing baseline data and interpretation of management outcomes. As it does with many of its individual programs, USGS coordination of this work within the larger framework of a national river monitoring system would enhance both activities.

Likewise, a USGS river monitoring system would be enhanced by partnerships with recently proposed environmental observatories. These include the National Ecological Observatory Network (NEON) and the joint proposal for hydrologic observatories and advanced environmental measurement technologies by the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) and the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER). The USGS should seek to collaborate with these groups, and integrate contributions from these efforts within its river monitoring sampling design.

River Monitoring—Measurement Technologies

Recommendation: The USGS must remain at the forefront of river monitoring technologies. The development of new cost-effective instrumentation and measurement techniques for monitoring physical and biological variables is an essential component of a river monitoring system.

To develop a modern river monitoring system, the USGS also needs to be at the forefront of river measurement technologies. Advances in sensor and network technologies, wireless communications, and remote sensing are likely to change the way environmental monitoring is done in the future. Extensive research on embedded networked sensing for environmental applications is underway in both laboratories and field stations. For example, researchers at the James Reserve in Southern California have been testing a diversity of wireless and robotic networked instruments since 2002. These include aquatic sensors; acoustic animal sensors; instruments for collecting root, soil, and fungi data; and live webcams. Similar efforts have begun at the Santa Margarita Ecological Reserve, also in Southern California, and field experiments are underway in snow-dominated environments as well.

Thus, opportunities will exist to gather more data and increase the variables that can be monitored, all at lower costs than today. Sensors will be able to communicate with one another in order to increase or decrease monitoring frequency as appropriate, thereby lowering costs and increasing the quality of the information flow. The USGS must continue to investigate and invest in new river monitoring technologies to develop a cost-effective sampling design for river monitoring and to enable integration of these data with those from sensor networks at various scales.

The USGS is already heavily involved in evaluating new technologies for NSIP. Increasingly, acoustic methods are being used to map the three-dimensional flow velocity structure of rivers, rather than simply estimating area-integrated variables such as discharge. As part of the USGS HYDRO-21 program, noncontact measurement technologies, including Doppler radar techniques, are being tested for direct and continuous noncontact measurements of river flows (Costa et al., 2000). Novel techniques, combining concepts in river hydraulics and fluid mechanics, are being employed to derive river stage-discharge ratings from first principles, rather than empirically through repeated (and costly) direct discharge measurements (Kean and Smith, 2005). These efforts need to be broadened to include all elements of river monitoring, and a continual program of measurement technology assessment must be implemented as an integral part of a 21st-century river monitoring system.

A greater emphasis on the use of remote sensing techniques for river monitoring is also needed by the USGS. Terrestrial, airborne, and satellite remote sensing technologies have significant potential to advance river science by providing observations related to a river's temperature, water quality, and ecosystem functions, and the vegetation type and physical characteristics of riparian areas, with better spatial coverage than attainable with in situ measurements. One of the most promising technologies is airborne light detection and ranging (lidar). As part of the Federal Emergency Management Agency's (FEMA) Map Modernization program for flood hazard mapping, the use of lidar-based measurements to create very high resolution digital elevation models of floodplain areas is becoming commonplace. Within the USGS, side-scanning terrestrial lidar is being used to map coastal bluffs; similar techniques could also provide a cost-effective approach for obtaining detailed information on river channels and their changes (e.g., due to streambank erosion).

Space-based remote sensing products for land surface monitoring, developed by NASA and other agencies (including the USGS); can also support river science activities. For example, the Enhanced Thematic Mapper Plus (ETM+) from the *Landsat 7* satellite provides high resolution (15-60 m) multispectral data to characterize land surface conditions. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's *Terra* satellite provide high (15-90 m) and medium (250-1000 m) resolution information on vegetation and land cover. These and other satellite and airborne remote sensing products are readily available to USGS researchers from the USGS Earth Resources Observation Systems (EROS) Data Center (see Chapter 3). EROS data archives, obtained in part in collaboration with other federal agencies, contain not only aerial and satellite remote sensing imagery but also maps, land cover data, and other derived products.

For river science, the USGS needs to be actively involved in developing ways to combine terrestrial, airborne, and satellite remote sensing information with in situ measurements at index reaches and study sites, to develop indirect means for mapping the physical and biological characteristics of floodplain and riparian areas along the river corridor. These efforts will require collaboration and cooperation with other federal agencies (e.g., FEMA and NASA), and should leverage existing interagency relationships and capabilities of the EROS Data Center.

INTEGRATED DATA ARCHIVING, DISSEMINATION, AND MANAGEMENT

River science is an integrative science, requiring synthesis of measurements from diverse sources, collected over disparate time and space scales. In addition to streamflow data and point measurements of water quality, the suite of observations that support river science investigations include two-dimensional data and observations describing stream channel geometry, and time-varying data on bed forms, channel sediments, and the land uses and vegetative cover of riparian corridors and upstream drainage areas. Three-dimensional data describing flow velocity fields are also now available from innovative acoustic Doppler technologies and even four-dimensional measurements (i.e., time-varying three-dimensional fields) are both technologically and economically practical data forms with great potential value for river science.

The interdisciplinary needs for river science data—common to many agencies, institutions, and stakeholders—have the characteristics of a public good, and merit public support for not only data collection, but also archiving, maintenance, and dissemination. USGS information is frequently used to support and inform decision making. Decision support systems, as connectors between science and decision making, can be improved if the data are compatible with these systems (NRC, 1999b). Therefore, to maximize the value of the appropriate public investment in data, the design and implementation of enhanced data collection activities to support river science should carefully examine the opportunities and emerging technologies to standardize data collection protocols, carefully document quality assurance and quality control procedures and metadata, and exploit technologies for data sharing and virtual data warehousing.

In light of this variety of river science data and their multiple uses, this next section addresses how USGS databases that span multiple disciplines need to be modified to better store, manage, and disseminate river science data.

Recommendation: The USGS should include in its river science initiative an informatics component that includes developing a common data model for river science information that can be used to archive the diverse river science metadata and data. This data model should be developed in coordination with and capable of supporting other federal agency river science data needs. The data model should accommodate data from multiple sources, including nonfederal sources. Such a program would facilitate the integration and synthesis of river science data to address the diverse range of river science questions discussed in previous chapters.

Data Management Needs for River Science

For many river science questions, collecting data to address critical data gaps is just the first step; effective data management systems for the archival and dissemination of interdisciplinary datasets are also needed to facilitate the integration and synthesis that advance our understanding of river processes. River restoration, as described below, is a good example of how a data management system can greatly enhance the efficiency with which researchers and managers can understand the river system,

Government agencies and various stakeholders now accept river restoration as an essential complement to conservation and natural resource management. However, despite legal mandates, massive expenditures, and the burgeoning industry of aquatic and riparian restoration, many restoration activities have failed. Reasons include lack of (1) a solid conceptual model of river ecosystems; (2) a clearly articulated understanding of ecosystem processes; (3) recognition of the multiple, interacting temporal and spatial scales of river response; and (4) long-term monitoring of success or failure in meeting project objectives following completion. These problems suggest that the scientific practice of river restoration requires an understanding of natural systems at or beyond our current knowledge, and this presents a significant challenge to river scientists.

The National River Restoration Science Synthesis (NRRSS; http://nrrss.nbii.gov) Restoring Rivers.org project (http://nrrss.nbii.gov/) is an effort to facilitate integration and synthesis across multiple disciplines using diverse databases and models. The NRRSS maintains a database of more than 50,000 restoration projects from around the country. This database holds information on why projects were undertaken and how they were implemented and provides the opportunity for synthesis to understand the effectiveness of river restoration practices. This database provides much useful information for the evaluation of the effectiveness of river restoration efforts based on sound river science, and serves as an example of the synthesis that can be achieved through the use of integrated data management systems. Participants in the NRRSS have called for major efforts to develop national standards for reporting restoration and a national tracking system to ensure better coordination of restoration efforts and to facilitate effectiveness evaluations. They identified USGS as an appropriate candidate for spearheading this effort (Palmer and Allan, 2006).

The USGS Role in Data Management for River Science

From a wide range of studies related to river processes, considerable data resources already exist at the USGS. Much of the data is archived and disseminated through data management systems, including the NWIS, NAWQA program/Data Warehouse, NBII, The National Map, EROS-EDC (Earth Resource Observation Systems-Earth Data Center), and others. However, some of the data collected are in the individual holdings of scientists and thus data users have difficulty locating datasets that serve their needs. Even more importantly, data are archived in ways that make sense from the perspective of the study for which the data were collected, but that may not be conducive to integrated data analysis with other data types.

For river science, it is in the national interest for data holdings to be standardized and archived with sufficient ancillary information (metadata) that allows them to provide traceable heritage from raw measurements to useable information and allows the data to be unambiguously interpreted and used. Technological capabilities and measurement methods are advancing rapidly, yet synthesis of trends over time mandates standard, consistent, fully documented measurement protocols and the maintenance of data in systems that are accessible using the most current technology. Given the diversity of USGS river science information, this is a daunting information science (informatics) challenge. Nevertheless this challenge needs to be addressed if the capability for national synthesis is to be sustained.

A large number of federal agencies are involved in various aspects of river science data collection. Cooperation and coordination among these agencies and nonfederal partners is needed for the management and sharing of data in a clear, public, national way. Cooperative federal data initiatives, such as the Office of the Federal Coordinator for Meteorological Data, and the Subcommittee on Water Availability and Quality (SWAQ) of the Committee on Environment and Natural Resources of the National Science and Technology Council (NTSC) (the primary coordinating and planning group for water related science and technology in the federal overnment), offer lessons and experience to guide river science data needs. Emerging multiagency efforts such as NBII, The National Map Initiative, and NHDPlus serve as examples that can guide river science data management and coordination.

In principle, any of the federal agencies involved with river science could take the lead in coordinating data management and dissemination. There are, however, three compelling reasons why the USGS should be a leader in this area. First, the USGS has considerable expertise and experience in data management and dissemination, supporting systems such as NSIP, NAWQA, NBII, and The National Map. Second, the USGS, as a science agency, has a reputation for impartiality and quality. And third, the primary focus of the USGS is on earth science, which in its broad sense includes river science.

Existing Data Management Systems Supporting River Science Activities

A first step in designing standard data models that accommodate integrated archiving and dissemination of river system data is to consider how well existing data models and data management systems (of the USGS and other institutions, including private and commercial database management systems) support river science activities. What follows is an evaluation of these data systems, where we highlight both their strengths and limitations. Insights from this review motivate recommended design principles for an improved approach.

NWIS—NWIS (http://waterdata.usgs.gov/nwis/), the USGS Water Resources Discipline's flagship data system, has served daily USGS streamflow to the public and provided an internal USGS system for the distributed archiving and management of streamflow data for many years. It also contains NASQAN data. In many respects with NWIS, the USGS has led the way in making river science data publicly available. However, NWIS was designed at a time when computers and network bandwidth were much more limiting than today and when commercial database systems and web service capability were in its infancy or not existent. As a result, many of the features of NWIS appear primitive by modern standards, such as the limitation of data distribution via NWISWeb to 24 hour daily values rather than unit values recorded more frequently at stream gages, an implementation limitation adopted due to computer system limitations at the time computerized storage of streamflow data was developed.

NAWQA data warehouse—The NAWQA data warehouse (http://water.usgs.gov/nawqa/data/) has been developed to facilitate national and regional analysis of data from NAWQA study units. The data warehouse contains links to the following data:

- Chemical concentrations in water, sediment, and aquatic organism tissues and related quality control data (from NWIS);
- Stream habitat and community data on fish, algae, and benthic invertebrates;
- Site, well, and basin information associated with thousands of descriptive variables derived from spatial analysis like land use, soils, population density, etc.; and
- Daily stream flow and temperature information for repeated sampling sites (from NWIS).

In contrast with NWIS, the more recently developed NAWQA data warehouse was designed to make maximum use of the most current off-the-shelf software. Development was by USGS staff with expert consultants hired from the private sector. The warehouse uses relational databases and web services to extract information from data sources and transform and stage it for loading into the NAWQA databases, which provide read-only open database access that supports querying to facilitate integrative data analysis and synthesis.

NBII—NBII (http://www.nbii.gov) is a broad, collaborative program that provides increased access to data and information on the nation's biological resources. NBII links diverse, high-quality biological databases, information products, and analytical tools maintained by NBII partners and other contributors in government agencies, academic institutions, nongovernment organizations, and private industry. NBII uses a distributed, node-based architecture, with considerable diversity of information presented across nodes. This fulfills the needs of making data available, but the diversity of formats appear to hamper the integration and synthesis of information across the nodes. NBII was instrumental in helping to build the database structure for the NRRSS (http://www.restoringrivers.org).

Regional USGS databases—As noted in Chapter 3, a number of the USGS's river programs have their own databases. For example, LTRMP on the Upper Mississippi River System has the largest integrated database (2.2 million records) on the nation's largest river; it provides query tools and graphical browsers for a variety of datasets, and is used to produce decision support and synthesis reports. Where developed, such regional databases should be closely examined and compared for broader applicability.

The National Map—The National Map (http://nationalmap.gov) is the USGS's interactive map service intended to provide a consistent framework for serving the nation's mapping needs. The content that has been integrated into the national map is impressive; however, it is primarily geographic.

NHDPlus—NHDPlus (http://www.horizon-ystems.com/NHDPlus/index.htm) is an integrated suite of application-ready geospatial datasets that incorporate many of the best features of the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), the National Land Cover Dataset (NLCD), and the Watershed Boundary Dataset (WBD). The NHDPlus consists of nine components:

1. Greatly improved 1:100K National Hydrography Dataset;
2. A set of value-added attributes to enhance stream network navigation, analysis, and display;
3. An elevation-based catchment for each flowline in the stream network;
4. Catchment characteristics;
5. Headwater node areas;
6. Cumulative drainage area characteristics;
7. Flow direction, flow accumulation, and elevation grids;

8. Flowline min/max elevations and slopes; and
9. Flow volume and velocity estimates for each flowline in the stream network.

The NHDPlus is being developed by Horizon Systems, a contractor working for the EPA, with considerable USGS participation in the development team. Much of the stream reach information available in NHDPlus is particularly relevant for river science.

Arc Hydro—Arc Hydro was developed as a generic geographic data model for water resources and comprises hydrography, watersheds, the stream network, channels, and hydrologic time series. Recently this framework has been extended to groundwater. Arc Hydro has been implemented as a geodatabase schema and toolset using ESRI's ArcGIS geographic information system software. Arc Hydro provides a structured model for the representation of geographic surface and groundwater features that facilitates integrated analysis based on these features. The Arc Hydro structure provides a basis for hydrologic information systems and the nascent hydrologic information science.

Web-service-oriented data delivery—Much Internet-based data delivery involves browsers and portals. However, the Internet delivery paradigm based on web services is growing in use and capability. Web-service-based systems are being developed by some of the National Science Foundation (NSF) cyber infrastructure initiatives such as CUAHSI, CLEANER, Geosciences Observatory Network (GEON), and NEON. Web-service-oriented data architecture uses Internet-based object access protocols to enable access to data directly from application programs. This serves to make data available in the analysis environment of a scientist's choice, such as Matlab, Excel, or ArcGIS. The web services direct access model avoids the need to use a browser to access and download the data required for analysis from multiple sources. Web services integrate data delivery with analysis and provide a mechanism for integration across data holdings from different sources. To the extent possible, the USGS is encouraged to develop a data model that supports web service access to river science data.

Design Principles for USGS River Science Data Management Models

The examples presented above provide a survey of some of the database management systems available that are relevant to river science. Each has its strengths and weaknesses. No one of these could completely provide for the needs of river science. In developing river science data models to fulfill the needs of a USGS river science initiative, we suggest these systems be reviewed to determine which aspect of each could be adopted.

A common data model would provide an intellectual framework under which river science data holdings are catalogued and accessible. To develop such a model, a strategic plan put together by informatics experts from the USGS, other agencies, and academics needs to be developed. The notion of "dataspaces" (Franklin et al., 2005) extends information management beyond one integrated database into distributed information elements managed by different participants. The following characteristics of dataspaces merit evaluation as part of the common river data model framework:

- Management of a dataspace system does not assume complete control over the data in the dataspace.
- The dataspace encompasses all of the data and information in the organization regardless of its format or location.
- The key service provided in the dataspace is the cataloging of participant data elements. This cataloging provides basic information, including data quality that supports other dataspace services like searching and querying.
- Not every participant data source is necessarily interfaced to support all of the integrative functions available. The inclusion of these data sources is prioritized and approached as needed.

In designing a data management system for the archiving and dissemination of river science data, the data model should be constructed in accordance with the standards of the National Geospatial Data Infrastructure and should be based on sound, robust, and scalable relational database and geographic information science design principles that can be implemented using advanced commercial database technology. Implementation should include coordination with other federal agencies and nonfederal partners involved in river science and should incorporate analytic capability for scientists to efficiently query and use the data in the course of their research. Ideally the system should make river science data analysis easier so it becomes the preferred platform for data analysis and sharing, rather than a chore for scientists to have to load their data into at the end of a project. The data model implementation should facilitate the Internet dissemination of river science data approved for public use. To achieve this coordination and acceptance, we suggest that the system not be a centralized, single entity but rather a distributed confederation of participants, each responsible for and knowledgeable regarding their own element. The involvement of people fulfilling multiple roles (users, data providers, and analysts) working with the system is as important as the technology.

Whatever data models arise to support river science, one can confidently predict these needs will continue to evolve in unanticipated ways with the emergence of new problems, sensors, and assimilation techniques. The modern history of national data collection efforts offers vivid examples of data that has been "stranded" by technological innovations in database management. One example is the vast store of archived paper records from the national streamgage network that are ripe for data rescue (i.e., the conversion from paper to digital formats). Another example is the modernization of the EPA STORET system for managing water-quality data from a broad varying community of users. Challenges in incorporating data collected using historical protocols has resulted in the awkward use of Legacy STORET and Modernized STORET. The data management system to support an integrative river science should therefore be designed and structured to be adaptable and scalable in order to avoid stranding the next generation of river science data, as the information technologies continue their rapid pace of innovation and development.

The ultimate goal should be a common data model for river science information that fulfills the needs of the USGS, other federal agencies, nonfederal partners, and the public. This needs to include a system that is queryable, easy to use, and provides effective visualization and analysis capability. An open architecture data model is suggested to clearly and unambiguously document the data being presented. Another goal is the infusion of expertise into USGS river science staff, to the point that data management based on advanced relational database systems becomes part of the culture and business practices of the organization. Just as the USGS has historically piloted many innovative physical measurement methods, the USGS should invest in evaluating and testing new data management techniques and then training and disseminating the findings to individuals throughout the organization.

CONCLUSIONS

To provide long-term baseline science information on our nation's rivers, and to support research in USGS river science priority areas, new river monitoring and data management activities are essential for a USGS river science initiative. The USGS has historically provided unbiased fundamental river science data used to characterize river processes. Maintaining and expanding this capability is critical to the national need, particularly because long-term datasets on river hydrology, chemistry, and biota are essential for addressing future river problems that broadly affect the nation's economy and well-being. Some of these problems cannot be anticipated in detail now, but baseline information will be needed to investigate causes of river changes at all scales. Expanded monitoring is also needed to address the USGS river science priority areas identified in Chapter 4. Currently, the science data gaps that exist are an impediment to progress in these areas, and future science advances are predicated on new river monitoring and data management efforts.

Expanded data monitoring for river science should focus on developing integrated datasets on the hydrologic, geomorphic, chemical, biological, and ecological conditions of rivers. This objective could be achieved in part through the establishment of reach-scale monitoring sites. To plan and implement a 21st-century system for river monitoring, the USGS will need to define specific monitoring goals, and develop a scientific framework for sampling to meet these goals. Advancing measurement technologies to support river monitoring is important to this effort, as is partnering and cooperation with other federal and local agencies, since many groups collect and archive data relevant to river science.

Archiving, disseminating, and managing integrated datasets for river science is a challenging problem. However, advances in information technologies are transforming science by making complex data archives easier to access and analyze. An informatics component is needed to develop a common data model for efficiently archiving and distributing datasets and metadata. Conceptualizing such a data model, and putting it into practice, will require an ongoing, long-term effort on the part of the USGS as an institution, as well as its individual disciplines. Coordination and partnership with other federal agencies and nonfederal partners is important. The coordination necessary to achieve the goal of a common data model for river science may serve to stimulate integration between fragmented river science activities across the federal agencies, the non-governmental sector, and within the USGS, and provide a basis for a coordinated interdisciplinary management approach, as considered in the following chapter.

6

Coordinating River Science Activities at the USGS

Within the USGS organizational structure, all the disciplinary building blocks exist for a USGS river science initiative. Still, bringing together these elements to create a USGS river science initiative is a challenging task. How effectively the USGS does this will play a large part in determining the success of its river science activities. This chapter identifies institutional challenges for the USGS in implementing a river science initiative, and provides some recommendations to help guide this process.

Today, research on rivers at the USGS takes several forms, namely bottom-up, top-down, and customer driven. It can be bottom-up, driven by individuals or small teams of investigators, often from the National Research Program (NRP). A recent example of this is the "so-called Lagrangian study," which followed a slug of water as it moved down the Mississippi River and into the Gulf of Mexico to test whether nitrate is transported conservatively, without denitrification, in large rivers (Goolsby and Battaglin, 2001). This study was initiated as part of the larger National Water Quality Assessment (NAWQA) program to address gaps in our understanding of the Gulf hypoxia problem. USGS river science research is also top-down, as in the case of the Platte River Priority Ecosystems Science study (http://mcmcweb.er. usgs.gov/platte/index.html). Here, a team of scientists from several USGS disciplines was formed to better understand the physical and ecological changes affecting endangered species within the river. Finally, USGS river research can be customer-driven. This includes much of the science done to support multiagency regional efforts such as CALFED, the Everglades, coastal Louisiana, the upper Mississippi River, and the Chesapeake Bay, where the USGS contributes river science and measurement expertise. This customer-driven research also includes numerous, more focused research projects supported by management agencies such as the Fish and Wildlife Service and National Park Service and their state equivalents, and primarily carried out in the Biological Resources Discipline (BRD) Science Centers.

All of these kinds of river science activities can be part of a coherent and successful USGS river science initiative. Furthermore, each approach presents opportunities for close coordination and interdisciplinary collaboration among the USGS disciplines as well as useful linkages with the work of other federal agencies. The challenge for a USGS river science initiative will be to engage all disciplines within its structure to do integrative multidisciplinary research.

Serious institutional obstacles within the USGS impede collaboration among disciplines. Perhaps the most fundamental of these is that the local or district offices of each discipline are usually not colocated. Most geology discipline scientists are in the three regional centers in Reston, Virginia, Denver, Colorado, and Menlo Park, California, and many geography discipline scientists are at the Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, South Dakota, or the Mid-Continent Geographic Science Center in Rolla, Missouri. Water resources discipline scientists, in contrast, are located at these regional centers but also in 54 water science centers throughout the country. Most of the biological resources scientists are located at 18 science and technology centers and to a lesser extent in cooperative research units at 40 universities around the country. Thus, despite goodwill and interest in collaborative work, the opportunities for the kinds of informal discussions that often lead to interdisciplinary projects are limited.

There are a few places in the USGS organization where several disciplines are colocated in a meaningful way. For example, the BRD's Fort Collins, Colorado, Science Center and Columbia Environmental Research Center have five and three hydrologists, respectively. The Southwest Biological Science Center's Grand Canyon Monitoring and Research Center has a staff that although modest in number, has nearly equal numbers of biologists, hydrologists, and Geographic Information Systems (GIS) specialists/geographers. Other centers are not as well supplied, such as the Leetown, West Virginia, Biological Science Center, which lists no hydrologists on staff (http://www.lsc.usgs.gov/stafflist.asp) even though it has major research projects in and around rivers. Similarly, only geographers staff the Mid-Continent Geographic Science Center, even though it is working on hazards and land changes. Likewise, the Upper Midwest Environmental Science Center has no hydrologists on staff, although it does have four statisticians, four chemists, and three physiologists along with specialists in contaminants, limnology, sediments, and GIS (Barry Johnson, USGS, written communication, March 2006).

Of the approximately 4000 Water Resources Discipline (WRD) employees, there are about 24 whose title is ecologist, and slightly over 100 whose title includes biologist (USGS, 2006a). Half or more of these positions presumably reside in the water science centers; each center has at least one biologist or ecologist. Most of these were hired to work on NAWQA projects, where ecological studies are being conducted in 42 study units. However, increasingly they have been involved in cooperative projects with corresponding state and local governments (Donna Myers, chief, NAWQA program, oral communication, March 2006). Recent examples include "Streamflow Characteristics and the Basis for Ecological Flow Goals" (New Jersey), "Landforms and Ecology" (Tennessee), "Characterization of Natural Flow Regimes for Rivers in Southern New England" (Massachusetts), "Wetlands in Central Florida," "Shamokin Creek Acid Mine Drainage [Land-use, Hydrologic, Chemical, and Ecological] Assessment" (Pennsylvania), "Nanticoke Creek Restoration" (Pennsylvania), and Good Hope Dam Removal (Pennsylvania). This trend will likely continue.

Each of the four WRD regions has a regional biologist, and at headquarters the Ecological National Synthesis Section has five scientists whose expertise and responsibilities are primarily ecology. The National Water-Quality Laboratory includes a Biological Unit with three biologists and a chemist supervisor who analyze biological samples from NAWQA and other programs. Ecology is one of six disciplines in the National Research Program (NRP) and includes 22 projects (USGS, 2006b).

Thus, many building blocks to foster a successful environment for river science are already in place, and different disciplines appear to be working together on a wide variety of projects wherever the institutional framework permits. However, to be successful in pursuing a broader river science initiative, the USGS must continue to build the institutional capacity for such work. The USGS must find ways to integrate its river science research efforts to provide avenues for bottom-up, top-down, and customer-driven research activities to flourish. Facilitating the development of interdisciplinary teams should be imperative.

River science would not have to be a formal program at the USGS, although it could be justified as one based on its centrality to the USGS's mission. As noted in Chapter 3, interdisciplinary USGS activities include programs, such as the Science Impact Program; less formal initiatives such as the Priority Ecosystems Science (PES) Initiative (includes effective collaborative projects in rivers, estuaries, and wetlands) and the Amphibian Research and Monitoring Initiative; and highly decentralized but coordinated themes, such as global change research and human health activities. In the following discussion, we use the term "initiative" without any presumption about the degree of the institutional formality of such an initiative.

Having a river science initiative in no way implies that all river science projects would be run out of a central office. River science projects have evolved independently within the NRP, the BRD Science Centers, the WRD Science Centers, the PES Initiative, and elsewhere. It is unrealistic to assume that adding, for example, biological monitoring to an existing hydrologic monitoring study in a WRD Water Science Center, or vice versa in a BRD science center, should immediately move a project administratively to a new program.

Even initiatives run nominally from the director's office are generally coordinated by one of the disciplines (e.g., the PES Initiative is coordinated out of the associate director for biology's office). Given the modest staff of the director, it is reasonable to assume that river science would be no exception to this model. Like the PES, however, whose team leaders are sometimes from the WRD (e.g., Chesapeake Bay) and sometimes from the BRD (e.g., Everglades), future river science initiatives would logically involve the water resources and biological resources disciplines, with supplemental involvement from the geology and geography disciplines as well.

Although all the scientific disciplines would contribute to a USGS river science initiative, the Water Resources and Biological Resources Disciplines are clearly the most involved in river science projects. The WRD has several unique organizational and programmatic elements that could facilitate implementation of a river science effort. Outside the USGS, the WRD is perhaps best known for operating the network of nationally consistent stream gages that make up the National Streamflow Information Program (NSIP). The organizational structure of NSIP involves coordination among water science centers and provides invaluable connections and robust partnerships (including funding through the Cooperative Water Program) for information delivery and technology transfer to meet local, state, and regional needs. Overlaid on core data collection functions, the science centers also combine interdisciplinary technical expertise supporting the analysis of hydrologic, chemical, biological, and geomorphological data, and information generation through interpretive studies tailored to meet the needs of local and regional partners and decision makers.

The national network of water science centers is the "ground-based" location of day-to-day service delivery. The presence of members of the Water Resources Discipline in the science centers provides a rich infrastructure to deliver the interdisciplinary capabilities of USGS to local partners, cooperators, stakeholders, and decision makers. Moreover, the science centers programs link the NRP to local needs through a two-way exchange of information, which is often enhanced by partnerships with state-based networks through the State Water Resource Research Institute Program (http://water.usgs.gov/wrri/). As described in the NRC report on hydrologic hazards science at the USGS (NRC, 1999c), the science centers provide cooperators with science information on local problems through interpretative studies, which integrate their data collection and research
The BRD also brings strengths to the table for coordinating river science projects. Its regionally distributed biological science centers often bring decades of experience on individual rivers, estuaries, and lakes. The Great Lakes Science Center traces its origins to 1927, the Leetown Science Center to 1931, and the Patuxent Wildlife Research Center to 1935. Centers such as the Upper Midwest Environ-

mental Sciences Center, the Columbia Environmental Research Center, and the Fort Collins Science Center are doing important work on the relationships among river flows, levels, and water quality and the habitat availability and biotic responses of riparian and aquatic species. Hydrologic monitoring and research have been, and will continue to be, added to the historic research on wildlife biology and habitat at these centers.

The Cooperative Research Units Program of the BRD also has considerable interdisciplinary experience. Created in 1935, these units are a partnership among the BRD, state natural resource agencies, Land-Grant universities, and the Wildlife Management Institute. Because they are located on university campuses, they not only conduct research on renewable natural resource questions but also participate in graduate education, provide technical assistance and consultation to natural resource agencies, and provide continuing education for natural resource professionals. The connection to universities is particularly noteworthy, as it permits the training of some of the river science professionals that the USGS will need in decades to come, especially in the field of natural resources management.

As with any new concept, the quality of leadership of a river science initiative will be vital to its success. Aside from being highly competent in their own fields, leaders should have a track record of working well across disciplines within and outside of the USGS. They should also have experience and interest in both basic and applied science.

A range of funding mechanisms also needs to be found if a healthy, dynamic initiative is to be begun and continued. Experience has shown that many natural scientists are enthusiastic about participating in interdisciplinary projects. However, many such endeavors have foundered from inadequate funds to support monitoring, modeling, and analysis of the multiple parameters necessary to achieve understanding of complex river systems. Such funding could come from internal or external sources, or both.

In conclusion, there probably is no single best institutional place for a river science initiative. River science covers a wide variety of basic and applied research with a broad range of federal, state, and local partners. The approach to dealing with river science must be born of an institutional culture that fosters integrative cooperative research. Coordination mechanisms within the USGS should take into consideration these different circumstances, and take advantage of the unique strengths of the many WRD and BRD river science programs and the related programs of the other disciplines. Whatever the approach taken, the fragmented nature of the USGS's current approach to river science needs organization and focus. A river science initiative that contributes fully to national needs will likely require innovative managerial approaches that form interdisciplinary research teams/groups that, if not housed together, are regularly brought together to plan, direct, and execute a USGS river science program.

Recommendation: The USGS should employ innovative managerial approaches to combine the best elements of existing Water and Biological Resources river programs, and other USGS programs, and refocus a portion of existing research and field team efforts around examining and answering nationally important river science questions.

This refocusing can and should take advantage of the outstanding two-way flow between WRD research groups and local offices as well as place-based experience and long-term datasets of some of the BRD Science Centers and PES sites. It should build on the consistent data collection standards, mapping, and national synthesis strengths of the USGS.

A USGS river science initiative should be the core of a multistakeholder cooperative effort. It is essential that the leadership of this initiative embrace and foster existing and new relationships with other federal agencies, state and local agencies, and educational institutions.

7

Recommendations

Human activities have changed rivers throughout our nation. Few rivers are pristine; most large ones have been dammed. Disturbances in natural flow regimes have led to problems, including enhanced sediment erosion and transport, loss of ecological diversity, declines in commercial fisheries, non-native species introductions, and reduced water quality. The beneficial use of river goods and services and river and riparian ecosystem health is a concern at local, regional, and national scales. Rivers cross state and international boundaries, and actions taken in one state have impacts elsewhere.

NATIONAL RIVER-RELATED NEEDS, CHALLENGES, AND DRIVERS

Current national river-related policy and management drivers and challenges include ecological restoration (including dam removal), relicensing of hydropower facilities, invasive species, water allocation, climatic variability, urbanization and other land-use changes, and water quality. There have been notable federal initiatives designed to address some of these issues. However, there remains a national need for science to support policy and management decision making that addresses conflicts over use of river resources and the best ways to ensure river ecosystems remain viable both now and in the future.

RIVER SCIENCE DEFINED

River science is the study of processes affecting river systems. The primary goal of river science is to develop a predictive framework among linkages between fluvial and ecological processes and patterns at multiple scales—an interdisciplinary scientific enterprise. Unlike other emerging sciences, the spatial and temporal boundaries of river science problems are defined by the characteristic spatial and temporal scales of the problem, from local and short-term, to national and long-term. Because of the complexity of rivers, an interdisciplinary, process-based, multiscale approach to studying rivers is needed to support policy-relevant decision making for the nation.

WHAT THE USGS BRINGS TO RIVER SCIENCE

Among federal agencies, the USGS is well poised to be a leader in river science. It historically has provided impartial policy-relevant data to the nation, leading all federal agencies in collecting hydraulic data on rivers, monitoring river conditions, and mapping the nation's mineral and water resources. It has an established data distribution infrastructure to provide quality data to the nation, multiple disciplines, and an organizational structure that engages in research at local to national scales. The USGS has a clearly well-defined responsibility to assist society in addressing science issues associated with rivers, and provide policy-relevant and policy-neutral information and understanding. Finally, river science spans traditional core scientific disciplines of the USGS—hydrology and hydraulics, sediment transport, biology and ecology, aquatic chemistry, geology, and resource mapping. As such, the USGS is uniquely positioned among federal agencies to draw from the disciplinary expertise throughout its organization to provide needed integration and synthesis.

Thus, the overall design principle for a USGS river science initiative should be to deliver objective policy-relevant science information in critical areas where the nation's gaps in understanding intersect with the USGS's strengths and missions. Other recommendations in this report may be viewed respectively as scientific, monitoring, data management, and institutional design principles.

Recommendation: USGS river science activities should be driven by the compelling national need for an integrative multidisciplinary science, structured and conducted to develop a process-based predictive understanding of the functions of the nation's river systems and their responses to natural variability and the growing, pervasive, and cumulative effects of human activities.

Recommendation: The USGS should establish a river science initiative to bring together disparate elements of the USGS to focus its efforts to deal with growing river science challenges. The initiative should build upon the USGS's history, mandate, and capabilities. It should take advantage of key attributes of the institution, such as its

1. mission as provider of unbiased science information,
2. multidisciplinary staff,
3. data collection and monitoring expertise,
4. experience in science synthesis at many scales, and
5. organizational structure that combines national research programs with state-, watershed-, and university-based cooperative programs. In carrying out the initiative, the USGS should closely coordinate with other federal agencies involved in river science and related activities.

SCIENCE PRIORITY AREAS FOR USGS RIVER SCIENCE

Society has a clear need for river science, and the USGS has a variety of strengths and capacities that can be brought to bear on these needs. The intersection of society's needs and the USGS's strengths suggest a number of priorities for USGS river science. These suggested science priorities are grouped into crosscutting activities and topical focus areas where recommendations for USGS research are offered.

Crosscutting Science Priority Areas

The following two recommendations relate to disciplinarily crosscutting activities that would strengthen the holistic river science approach. Although they are posed individually, there is great potential for activities in these priority areas to enhance each other. These activities would underpin the USGS's science contribution to a broad national effort in river science.

Surveying and Synthesizing

River networks are intimately connected to the landscape and are integrators of climatic, geologic, and land-use processes within their watersheds. Throughout the nation, there are large regional gradients in climate, geology, topography, land cover, and human impacts. This extensive variation makes meaningful generalizations about how streams and rivers function challenging, and complicates how information collected in one river can be transferred to another, geographically distant river. Therefore, generating a national baseline survey that characterizes the spatial variation in key landscape features and processes would provide insights into the controls of instream river processes and allow for more cross-site comparisons.

A multidisciplinary survey and mapping of rivers and streams should provide a preliminary structure of multiple information layers at a reach scale. This stratification of information would be based upon readily available data, including climate, topography, soils, and geology. It should also include land-use and human alteration information, such as upstream diversions and impoundments that alter the flow regime. Many other elements necessary for this collection of data layers are now available in the National Hydrography Dataset products that are under development in partnership with the Environmental Protection Agency (EPA). Ultimately, this mapping effort would provide a nationally useful resource for risk-based analyses of floods, invasive species spread, and many other issues.

Recommendation: The USGS should survey and map the nation's stream and river systems according to the key physical and landscape features that act as determinants of hydrologic, geomorphic, and ecological processes in streams and rivers. This synthesis will provide a scientific baseline that can be used to support many regional-scale river science questions and afford geographic information of use to state and federal agencies, academia, and the public.

Modeling River Processes

Quantitative models that integrate physical, chemical, and biological processes provide detailed information on pathways and interactions that are difficult to measure directly in the field or whose characteristics change over time. Models complement point measurements and surveys by interpolating across the data and providing a mechanism to predict future changes. The USGS has a 40-year history of developing mathematical models of natural systems, including estuarine ocean circulation, surface-water runoff and river hydraulics, groundwater flow and solute transport, sediment transport, biological processes in streams, and groundwater and surface-water interaction. The USGS is unique among federal agencies for its breadth of modeling applications.

Potential applications of predictive integrated models are many. The construction of ecohydrologic models that focus on the structure of streamflows coupled to models linking flow to watershed and meteorological variables could be used to test the physical and ecological response of river systems to changes in flow regime with changing climate or anthropogenic drivers. These models, if properly multidisciplinary and robust, could be invaluable in river restoration, planning, and multiple water resources issues. Models can also be used to address how flow might be decreased by groundwater pumping or enriched in excess nutrients from agricultural fields.

Recommendation: The USGS should add capacity in developing predictive models, especially models that simulate interactions between physical and biological processes, including transport and transformation of chemical constituents, pollutants, and sediment.

These tools provide the underpinning for predicting ecological change.

Topical Science Priority Areas

The following recommendations are designed to address gaps in specific research areas for which improved scientific knowledge is needed. Each of these science activities will include enhanced monitoring and modeling, and will be key components of the overall river science framework.

Environmental Flows and River Restoration

The `nation is spending billions on riverine restoration and rehabilitation projects, yet the science underlying these projects is not currently well understood and thus the approaches and their effectiveness vary widely. Therefore, a fundamental challenge is to quantitatively understand how rivers respond physically and biologically to human alterations from dredging to damming, and to specifically address: What are the required environmental flows (i.e., flow levels, timing, and variability) necessary to maintain a healthy river ecosystem? And which biota and ecological processes are most important and/or sensitive to changes in river systems?

For future restoration projects to meet their goals, they should be adaptively managed. This requires long-term monitoring of quantitative measures of flow regime, groundwater activity, and ecosystem responses such as primary productivity and habitat diversity along targeted reaches. Quantitative models relating ecological function to flow regimes are also needed to allow natural resource managers and citizens to forecast the impacts of proposed water management decisions. These efforts need to go beyond just stating the potential impacts of policy and management decisions to actually assessing the outcomes these activities have on rivers. Improving and synthesizing the scientific information on environmental flows before, during, and after river restoration will likely lead to an improved ability to predict outcomes and thus more effective, cost-efficient habitat restoration.

Recommendation: The USGS should develop the means to characterize environmental flows in rivers by developing quantitative models that link changes in the ecological structure and function of river ecosystems (aquatic and riparian) to management-scale changes in river flow regimes.

Recommendation: The USGS should, in cooperation with and support of other federal agencies involved in restoration, serve as a leader to evaluate the scientific effectiveness of river restoration

approaches to achieve its goals, synthesizing results from past restoration efforts, and designing standard protocols for the monitoring and assessment of river restoration projects.

Sediment Transport and Geomorphology

Erosion, transport, and deposition of sediments in fluvial systems control the very life cycle of rivers and are vulnerable to changes in climate and human landscape alterations. Yet, compared to water-quality and -quantity information, there is relatively little available information on sediment behavior in river systems, particularly large-order reaches, to understand the evolution of such landscapes in response to the erosion and deposition of sediment. Basic research is needed on sediment transport processes, and there is a paucity of accurate flux measurements of bedload, suspended load, and washload accompanied by flow velocity and water temperature.

To assess sediment fluxes, sediment transport technology needs to be advanced by the USGS in partnership with other research entities. These advances could be applied to problems such as determining the risk of contaminated sediment resuspension, designing and maintaining flood-control channels, predicting channel behavior, understanding sedimentation and hydraulic roughness in mountain channels, restoring and re-meandering previously channelized streams, assessing the impact of dam removal on river sedimentation and habitat, estimating flows needed for removing sand and silt from gravel-bed streams, and improving sedimentation management in lakes and reservoirs. Knowing the science of these sediment-related processes is critical to the multibillion-dollar efforts to restore wetlands, reestablish flow regimes, and maintain river reaches for transport.

Recommendation: The USGS should increase its efforts to improve the understanding of sediment transport and river geomorphology in the nation's rivers. Activities should include advancing basic research on sediment-transport processes, developing new technologies for measuring fluxes of bedload, suspended load, and wash load, and monitoring flow velocity and water temperature associated with such sediment transport conditions. Through these activities, the USGS can provide key information and tools to predict channel morphodynamics, develop methods to mitigate future problems arising from sediment movement, and play a guiding role in multiagency efforts to deal with the increasingly important national sediment challenges.

Groundwater and Surface-Water Interactions

River flows throughout the nation are affected when groundwater that normally discharges to rivers is captured for agriculture or other uses. Yet few of the USGS's 7400 active stream gages or hundreds of monitoring wells incorporate data on groundwater and surface-water exchange. Limited investigations have been done on the end members of potential hyporheic interactions—large-scale effects of water supply developments adjacent to large rivers and detailed hyporheic interactions on first-order streams—but the full continuum of how groundwater and river water interact is relatively unknown.

The USGS has the tools, datasets, and existing networks that make it a logical place to focus resources to investigate stream-groundwater exchange processes at a national scale. The USGS has been a leader in developing many hydrologic methods and tools used to characterize groundwater and surface-water interactions. This, combined with the USGS's extensive streamgaging network and synoptic survey datasets, provides an important foundation. The Lake and Reservoir Studies Program of the USGS, with some modification, provides a template for the development of an aggressive data mining effort and provides approaches to new field instrumentation of exchange rates.

Recommendation: The USGS should expand its current river monitoring and river study programs so they fully integrate the floodplain, channel, and groundwater, and the exchange of water between these systems (hyporheic exchange). The exchange of water between groundwater and rivers needs examination and quantification at multiple scales in a range of different hydrologic and geologic settings, as this process is a key component influencing river discharge and water quality, geomorphic evolution, riparian zone character and composition, and ecosystem foundation, maintenance, and restoration.

INTEGRATED DATA COLLECTION AND RIVER MONITORING

Monitoring our nation's rivers is the foundation of USGS's contribution to river science. Historically, the USGS has been a leader in river monitoring, distinguished for its scientific rigor, quality control, interpretative products, and innovative monitoring techniques and instrumentation. Therefore, the USGS is well positioned to fulfill the growing need to concurrently monitor hydrologic, geomorphic, chemical, and ecological river conditions.

Currently, streamflow data are available for many higher-order river systems, but data on water quality, sediment transport, biology, and ecology are often lacking. To make gage data more useful for river science initiatives, the USGS should investigate cost-effective ways to collect more integrative biophysical data. Among these efforts, the USGS should consider the incorporation of *index biological reaches*, where coupled measurements of river flows, groundwater levels and fluxes, and water quality are combined with riparian cover mapping. The USGS should prioritize based on those variables with broad science and management applications, and seek opportunities to collaborate with other programs that monitor rivers so efforts build on each other and do not duplicate one another.

By building on its existing capabilities and leading an effort to enhance river monitoring to fill the science data gaps in critical or neglected areas, the USGS will be able to better support all its priority research areas in river science.

Recommendation: The USGS should expand its monitoring activities on rivers to better incorporate river physical, chemical, and biological conditions within its existing river and streamflow monitoring programs. Its goals should include development of a 21st-century river monitoring system for data collection, transmission, and dissemination.

Enhancements in Biological Monitoring

Recommendation: Expanding the collection of biological and ecological data at streamgaging sites is needed to develop integrated biophysical datasets for river science. However, fundamental questions remain on how to implement a monitoring program to support national and regional synthesis. The USGS should continue its efforts to define relevant monitoring activities for national implementation, while expanding biological and ecological monitoring in a targeted fashion to address clearly defined regional data needs.

Enhancements in Sediment Monitoring

Recommendation: Leveraging the infrastructure of the streamgaging network, the USGS should greatly expand sediment monitoring of the nation's rivers. To meet the growing needs for sediment data, the USGS should take the lead in developing a comprehensive national sediment monitoring program.

Reach Monitoring Approach

Recommendation: An index reach monitoring approach would help address many data needs for USGS river science priorities. The USGS should begin efforts to design and implement sampling plans on reach scales to integrate monitoring of physical, chemical, and biological condition for river science investigations.

River System Monitoring—Sampling Design

Recommendation: For the design and implementation of a coordinated river monitoring system, the USGS should develop specific monitoring goals and objectives for building on its existing infrastructure. The USGS should prioritize these activities based on those variables with broad science and management applications.

River System Monitoring—Partnering in Monitoring Efforts

Recommendation: The implementation of a USGS river monitoring system should be informed by the data and science information gaps limiting effective policy and management decision making of other mission-oriented government agencies at federal, state, and local levels, as well as nongovernmental organizations and academic research institutions. Partnering with these groups to design and implement scientific data monitoring in support of site-specific management and research objectives must be a component of USGS river monitoring.

River System Monitoring—Measurement Technologies

Recommendation: The USGS must remain at the forefront of river monitoring technologies. The development of new cost-effective instrumentation and measurement techniques for monitoring physical and biological variables is an essential component of a river monitoring system.

DATA ARCHIVING, DISSEMINATION, AND MANAGEMENT

Integrative river science is supported by diverse measurements and observations. In contrast to streamflow data and point measurements of nutrient concentrations, observations to support river science include two-dimensional data and observations describing stream channel geometry, time-varying data on bed forms, channel sediments, and the land uses and vegetative cover of riparian corridors and upstream drainage areas. Three-dimensional data describing flow velocity fields are now available from innovative acoustic Doppler technologies that have been enhanced by the USGS, and even four-dimensional measurements (i.e., time-varying, three-dimensional fields) are both technologically and economically practical data forms with great potential value for river science. The USGS maintains and stores considerable information in databases from the National Water Information System (NWIS), National Water-Quality Assessment (NAWQA) Program, National Biological Information Infrastructure (NBII), Earth Resource Observation Systems-Earth Data Center, and The National Map.

It is in the national interest for river science data holdings to be standardized and archived in a consistent way with sufficient ancillary information (metadata) that allows it to provide traceable heritage from raw measurements to useable information and allows the data to be unambiguously interpreted and used. Coordination and cooperation among the federal resource management agencies and their nonfederal partners will be critically important as the scope, scale, and intensity of data needs to support river science evolves. No single federal agency can collect, quality assure, manage, and disseminate all data and observations relevant for river science. Yet all federal agencies, nonfederal partners, and stakeholders with an interest in river science data will benefit from access and availability of accurate, reliable, and well-documented data. A common data model would provide an intellectual framework under which river science data holdings are catalogued and accessible. To develop such a model, a strategic plan put together by informatics experts from the USGS and other agencies and academics needs to be developed.

Recommendation: The USGS should include in its river science initiative an informatics component that includes developing a common data model for river science information that can be used to archive diverse river science metadata and data. This data model should be developed in coordination with and capable of supporting other federal agency river science data needs. The data model should accommodate data from multiple sources, including nonfederal sources. Such a program would facilitate the integration and synthesis of river science data to address the diverse range of river science questions discussed in this report.

ORGANIZING AND MANAGING RIVER SCIENCE AT THE USGS

River science at the USGS and elsewhere covers a wide variety of basic and applied research and usually incorporates a broad range of partners. Because the USGS has strengths in many of the subdisciplines of multidisciplinary river science, there may be no single best institutional place for a river science within the current structure of the USGS.

Future river science coordination mechanisms within the USGS should incorporate certain key strengths within existing USGS programs. These include place-based experience and long-term datasets of some of the Biological Resources Discipline (BRD) Science Centers and Priority Ecosystems Science sites, the two-way flow of information between the Water Resources Discipline (WRD) personnel doing research and those doing applied science, the close links with universities of the BRD Cooperative Research Units and many of the WRD

Science Centers, and the close ties between the BRD Science Centers and other federal agencies and between the WRD Science Centers and state and local agencies. These coordination efforts should work closely with programs within the USGS's Geography Discipline to build on the wealth of existing mapping capabilities. They should also build on the consistent data collection standards, mapping, and national synthesis strengths of the USGS.

Overall, the current fragmented nature of the USGS's approach to river science needs organization and focus. Any managerial approach that addresses river science must be born of an institutional culture that fosters integrative cooperative research. An initiative that contributes fully to regional and national needs will require interdisciplinary research teams that, if not housed together, are regularly brought together to plan, direct, and execute USGS river science activities.

Recommendation: The USGS should employ innovative managerial approaches to combine the best elements of existing Water and Biological Resources river programs and other USGS programs, and refocus a portion of existing research and field team efforts on examining and answering nationally important river science questions.

Overall, society's linkages to rivers run deep and these linkages—from agriculture to transportation and from water supply to recreation—drive a broad need for advances in river science. The USGS, by virtue of its unique strengths among the many actors in river science, has an important part to play in meeting this need. By showing leadership in monitoring, modeling, surveying, synthesizing, and data management—concerning topics such as environmental flows, behavior of sediment, and groundwater and surface-water interactions—the USGS can contribute a great deal toward answering some of the most difficult and interdisciplinary questions involving rivers. Wise application of the knowledge gained will lead to better, more informed policy and management decisions throughout the nation.

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Appendix A

Valuing River Ecosystem Services

The human dimension is increasingly recognized as a critical component of river science, especially in the realm of river restoration or conservation, where social choices must be made in the process of river management (Poff et al., 2003). Thus, the social sciences of economics, policy planning, and management are as relevant to river science as the natural sciences. Of particular importance is the notion—implicit in the discussion in Chapter 2—that society places a finite value on rivers, and the justification for allocating national resources to river science is clearly based on the flow of ecosystem services that rivers provide. However, placing an economic value on the flows of services so that allocations of public funds can be assessed by the usual benefit-cost metric is easier said than done. Here we present a brief summary of the problems that may arise when trying to value water-based ecosystems. For a more thorough treatment, refer to Young (2005), *Determining the Economic Value of Water: Concepts and Methods*.

Ecosystem services span a gradient from values based solely on the use of a system to pure nonuse values that are based on the existence of an ecosystem. The National Research Council report on ecosystem valuation (NRC, 2005b) classifies ecosystem services as direct, indirect, and existence values. *Direct* valued uses include water supply, transportation, recreation, and fishing. *Indirect* valued uses include flood protection, nutrient recycling, genetic material, and wetlands. *Existence* services are river services that provide the needed habitat to allow current biological ecosystems and their species to thrive.

The direct, indirect, and existence values apply regardless of whether the service is consumptive. For example, water supply and commercial fishing are consumptive services. In contrast, most transportation and recreation services are nonconsumptive. This distinction does not influence the valuation, but helps define the effect of incremental changes in the river ecology.

DIRECT VALUATION

Where water resources generate market-priced goods, a measure of their value is represented by their price, and the social surplus attributed to the water resource can be measured by the usual consumer's surplus measures. Examples are ecosystem services such as water purification or commercial fish production.

Assigning values to ecosystems and the nature of their supply by river environments lead to economic valuation problems. Most of the challenges on the supply side arise from the difficulty in assigning a particular service to a given set of river characteristics. In most systems that produce economic goods a direct causal relationship, termed a production function, can be assigned between inputs and outputs. This enables a change in a valuable service to be assigned to a change in a particular input. The low flow stage of the river in summer months is an example; however, changes in low summer flows influence many ecosystem services and the effect of increasing summer flows may depend simultaneously on the level of other factors. The integrated nature of river systems means that ecosystem production functions are not only hard to estimate, but may be an inappropriate concept for river ecosystems.

Ecosystem services that are directly related to the economy can usually be assigned an economic value based on market prices and a willingness to pay. An alternative basis of value is the willingness of a consumer to accept compensation. These two forms of valuation may differ widely, because with the latter basis of value, a person's income is not a constraint. A more familiar example to most people would be medical malpractice, where the willingness to pay and accept differ widely.

INDIRECT VALUATION

Nonmarket services have to be valued indirectly. There are three main approaches. The first includes stated preference methods such as contingent valuation (CV). The second relies on revealed preference methods that include hedonic methods using related goods, travel cost methods, and the cost of averting behavior. The third opportunity cost methods group measures a lower bound on social values by calculating the social cost of providing water related, nonmarket goods.

Despite the attention to sophisticated survey methods, CV is dogged by the problem of strategic answers from respondents who realize that, in the survey, they do not have to make trade-offs against a fixed income that are inherent in economic valuation. Despite these problems, contingent valuation provides accurate relative, if not absolute, values, and for many ecosystem services it is the only operational method.

Hedonic values are inferred by measuring the market values of associated goods or services. The values are expressed in terms of the cost of alternative market-based uses that are foregone in order to provide the nonmarket service. This relies on measuring indirect indicators of economic value by finding linked goods that are market priced. Travel time and expenditures on recreation are often used as hedonic measures. Another common method is to reveal the implicit value of the service by using the difference in house or land values with and without the ecosystem services.

Opportunity cost methods requires a strong basis in river science to link nonmarket and market goods through a river system. A good example is the valuation of reduced eutrophication levels in the Mississippi River. While the consequences are so widespread that they cannot be addressed by a single survey, the source of eutrophication can largely be traced to excessive fertilizer use in upstream catchments. However, measuring the incremental change in eutrophication from a given fertilizer change requires a clear scientific linkage, not only in terms of causation but also in the time and area of the river system. A study of the level of eutrophication in the Mississippi River found the level of fertilizer used by farmers in Midwestern river states was, along with the slope and erodability of the farmland, responsible for a large proportion of the initial eutrophic load in the river. The cost of reducing this initial load was calculated using the opportunity cost of reducing farm fertilizer use and the consequent loss in crop yield. This is a good example of the opportunity cost valuation method being used in conjunction with river science to arrive at the effective cost of reducing a given pollution level.

As an example of indirect valuation, river ecosystems have a significant role in reducing the risk of flooding and other water-based risks such as hurricane surges. While some risks can be measured directly in terms of market insurance rates, most flood risks have to be measured by combining the event frequency with the expected damage. Clearly, river science underlies both these calculations. The extent of flood damage for a given event has to be calculated by careful consideration of the stages that will result from different flood events, and the duration of the inundation. The cost of flood damage is often influenced by the duration. The frequency of flood events can only be assessed by a full watershed approach, which is the essence of river science.

EXISTENCE VALUATION

Many ecological products have value to many consumers without their use or consumption. Existence services may be rooted in cultural heritage values and concern for future generations, but many feel there is intrinsic value in knowing that there are wild and unique ecosystems, even though one may never experience them. For example, in the debate over whether to allow drilling for hydrocarbons in the Arctic National Wildlife Refuge, a miniscule percentage of those opposed to drilling have, or will ever, actually visit the refuge. The Endangered Species Act is one indicator of how the nation has put an existence value on native species.

The term "option value" (i.e., value that people place on having the option to enjoy something in the future), is commonly invoked where there is significant uncertainty about the sustainability of ecosystem functions and the possibility that some ecosystem characteristics are irreversible, once lost. The Precautionary Principle proposes an option conservative approach whenever outcomes are uncertain. One option example is ecosystem biodiversity, especially where one suspects that the ecosystem does not have the continuous degradation and recovery curve that is implicit in most economic calculations. If the ecosystem has the probability of a threshold hysteresis effect and irreversibility, option values would require its preservation.

There is also a viewpoint that argues that ecosystems have intrinsic non-anthropogenic values. However one may feel about this argument conceptually, the value of rivers to humans, measured by a money metric, seems essential if river ecosystem services are to effectively compete for public expenditures.

VALUATION OVER TIME

In addition to their current existence, many ecosystem goods have intergenerational equity concerns. Intergenerational values are based on the principle that future generations should have the same access to these goods as the current generation. This value function is the root cause of the interest in sustainability in general and sustainable river ecosystems in particular.

However, determining how to change economic values over time is non-trivial. River ecosystem services are largely flows of services that for a stable river system, change stochastically around a central tendency. The standard economic approach to such long-term valuation problems is to use a discount rate to express a time series of effects as an equivalent present value. Clearly, the level of the discount rate affects the importance of services that occur far in the future. There is a long established literature on social rates of discount. Where the basis of comparison is strictly financial, economists feel confident using the opportunity cost of invested funds as the discount rate.

However, for most river ecosystem services, a financial opportunity cost is inappropriate and forces an emphasis on services that occur in the near future. Several authors (e.g., Heal, 2001) draw the distinction between discounting future utilities and the standard financial discounting. Alternatives to financial discounting include hyperbolic discounting where the discount rate is systematically reduced over time. This method suffers from time inconsistency in which it can be shown that optimizing individuals in the future will not make the trade-offs predicted by the model. An alternative approach is to define a recursive utility function. In this specification, service users are reluctant to change their expected consumption of the service over time. Recursive utility is time consistent and can be combined with a subjective rate of discount and risk aversion. However, it is not often used because of the mathematical complexity of the function.

Getting consistent contingent valuation responses is complicated when one asks consumers to estimate future values for different generations. An indirect method of valuation can be performed by defining the current economic restrictions and reallocations that are needed to ensure future viability. By measuring the opportunity cost of these constraints on the economic system, we can measure a lower bound value that is currently politically acceptable.

In summary, the economic valuation of the wide range of ecosystem services provided by rivers presents many problems because of both the lack of market signals for many of the services and the difficulty in assigning direct causal effects to inputs into complex and interdependent ecosystems. However, there is a wide range of approaches that can provide reasonable valuations for many services and at least a consistent ordering of relative values for those services that are more difficult to value.

Appendix B

Key River Science Questions and the Data Required to Answer Them

	Riparian/ River Ecological Data (Reservoir and Riverine)								
Question & Parameter	Baseline Ecological Data	Index Conditions	Macroinverte-brate/Marine Invertebrate	Algae Distribution & Identification	Species Survey	Indicator Species	Behavioral Patterns	Micrometeorol-ogy (fluxes & isotopes)	Sap Flow
River Restoration:									
Will restoration of hydrologic and geomorphic patterns restore ecological processes?									
How do we evaluate the ecological effectiveness of different types of restoration efforts?									
What are the cumulative contributions of individual projects to overall watershed improvement?									
Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state?									

	Hydrological Data (Reservoir and Riverine)							
Question & Parameter	Groundwater Data	Hyporheic Zone Data	Hydrologic Connectivity	Surface Flow & Velocity Distribution	Surface-Water Flow & Timing	Water Quality (SW, GW, Hyporheic)	Age Dating & Natural Tracers	Precipitation & Other Meteorological Data
River Restoration:								
Will restoration of hydrologic and geomorphic patterns restore ecological processes?								
How do we evaluate the ecological effectiveness of different types of restoration efforts?								
What are the cumulative contributions of individual projects to overall watershed improvement?								
Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state?								

	Sediment Data (Reservoir and Riverine)				
Question & Parameter	Sediment Load	Sediment Disposition & Erosion Pattern	Sediment Size Distribution	Sediment Quality	River & Banks Surveys
River Restoration:					
Will restoration of hydrologic and geomorphic patterns restore ecological processes?					
How do we evaluate the ecological effectiveness of different types of restoration efforts?					
What are the cumulative contributions of individual projects to overall watershed improvement?					
Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state?					

	Bank/ Floodplain/ Snowpack/Historical Data							
Question & Parameter	Soil Types and Quality	Wetland Survey	Snowpack/ Headwaters	Land-Use Data	Historical Data	Remote Sensing	Conjuctive/ Nonconjuctive Use Data	Subsidence Data
River Restoration:								
Will restoration of hydrologic and geomorphic patterns restore ecological processes?								
How do we evaluate the ecological effectiveness of different types of restoration efforts?								
What are the cumulative contributions of individual projects to overall watershed improvement?								
Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state?								

	Economic Data & Assessment Tools					
Question & Parameter	Economic Valuation	Dam-Removal Models	Sediment Fate & Transport Models	Hydrological/ Sediment/ Ecological Models	Groundwater/ Hyporheic Zone/ Surface-Water Models	Other Models
River Restoration:						
Will restoration of hydrologic and geomorphic patterns restore ecological processes?						
How do we evaluate the ecological effectiveness of different types of restoration efforts?						
What are the cumulative contributions of individual projects to overall watershed improvement?						Watershed Model
Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state?						

Question & Parameter	Riparian/ River Ecological Data (Reservoir and Riverine)								
	Baseline Ecological Data	Index Conditions	Macroinvertebrate/Marine Invertebrate	Algae Distribution & Identification	Species Survey	Indicator Species	Behavioral Patterns	Micrometeorology (fluxes & isotopes)	Sap Flow
Riparian Functioning:									
What is the relationship between alteration of flow regimes (especially extremes) and success of invasive species?									
Can restoration of flow regime below dams, independent of sediment regime, restore native vegetation or aquatic species?									
How does flow interact with channel geometry and sediment grain size to influence success of invasive species?									
Can we differentiate groundwater losses from evapotranspiration losses to model surface water yield?									
Land-Use Changes:									
How can we improve predictions of effects of land-use change on flow, water quality, & sediment movement?									
How can we manage watersheds to improve water quality & ecology?									

	Hydrological Data (Reservoir and Riverine)							
Question & Parameter	Groundwater Data	Hyporheic Zone Data	Hydrologic Connectivity	Surface Flow & Velocity Distribution	Surface-Water Flow & Timing	Water Quality (SW, GW, Hyporheic)	Age Dating & Natural Tracers	Precipitation & Other Meteorological Data
Riparian Functioning:								
What is the relationship between alteration of flow regimes (especially extremes) and success of invasive species?								
Can restoration of flow regime below dams, independent of sediment regime, restore native vegetation or aquatic species?								
How does flow interact with channel geometry and sediment grain size to influence success of invasive species?								
Can we differentiate groundwater losses from evapotranspiration losses to model surface water yield?								
Land-Use Changes:								
How can we improve predictions of effects of land-use change on flow, water quality, & sediment movement?								
How can we manage watersheds to improve water quality & ecology?								

	Sediment Data (Reservoir and Riverine)				
Question & Parameter	Sediment Load	Sediment Disposition & Erosion Pattern	Sediment Size Distribution	Sediment Quality	River & Banks Surveys
Riparian Functioning:					
What is the relationship between alteration of flow regimes (especially extremes) and success of invasive species?					
Can restoration of flow regime below dams, independent of sediment regime, restore native vegetation or aquatic species?					
How does flow interact with channel geometry and sediment grain size to influence success of invasive species?					
Can we differentiate groundwater losses from evapotranspiration losses to model surface water yield?					
Land-Use Changes:					
How can we improve predictions of effects of land-use change on flow, water quality, & sediment movement?					
How can we manage watersheds to improve water quality & ecology?					

	Bank/ Floodplain/ Snowpack/Historical Data							
Question & Parameter	Soil Types and Quality	Wetland Survey	Snowpack/ Headwaters	Land-Use Data	Historical Data	Remote Sensing	Conjuctive/ Nonconjuctive Use Data	Subsidence Data
Riparian Functioning:								
What is the relationship between alteration of flow regimes (especially extremes) and success of invasive species?								
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	Economic Data & Assessment Tools					
Question & Parameter	Economic Valuation	Dam-Removal Models	Sediment Fate & Transport Models	Hydrological/ Sediment/ Ecological Models	Groundwater/ Hyporheic Zone/ Surface-Water Models	Other Models
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Land-Use Changes:						
How can we improve predictions of effects of land-use change on flow, water quality, & sediment movement?						Watershed Models
How can we manage watersheds to improve water quality & ecology?						Watershed Models

	Riparian/River Ecological Data (Reservoir and Riverine)								
Question & Parameter	Baseline Ecological Data	Index Conditions	Macroinverte-brate/Marine Invertebrate	Algae distribution & Identification	Species Survey	Indicator Species	Behavioral Patterns	Micrometeorol-ogy (fluxes & isotopes)	Sap Flow
Dam Removal:									
Can we predict ecological responses to dam removal, both upstream and downstream, across a range of channel sizes, dam heights, and physiographic settings?									
Are there conditions under which geomorphic and ecological systems cannot recover following dam removal?									
How do we model the erosion and transport of stored sediment downstream after dam removal as a function of sediment size and volume and river flow?									
Can we identify which dams are most vulnerable to damage due to climate change?									

	Hydrological Data (Reservoir and Riverine)							
Question & Parameter	Groundwater Data	Hyporheic Zone Data	Hydrologic Connectivity	Surface Flow & Velocity Distribution	Surface-Water Flow & Timing	Water Quality (SW, GW, Hyporheic)	Age Dating & Natural Tracers	Precipitation & Other Meteorological Data
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	Sediment Data (Reservoir and Riverine)				
Question & Parameter	Sediment Load	Sediment Disposition & Erosion Pattern	Sediment Size Distribution	Sediment Quality	River & Banks Surveys
Dam Removal:					
Can we predict ecological responses to dam removal, both upstream and downstream, across a range of channel sizes, dam heights, and physiographic settings?					
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	Bank/ Floodplain/ Snowpack/ Historical Data							
Question & Parameter	Soils Types and Quality	Wetland Survey	Snowpack/ Headwaters	Land-Use Data	Historical Data	Remote Sensing	Conjuctive/ Nonconjuctive Use Data	Subsidence Data
Dam Removal:								
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Can we identify which dams are most vulnerable to damage due to climate change?						Watershed Models

	Riparian/ River Ecological Data (Reservoir and Riverine)								
Question & Parameter	Baseline Ecological Data	Index Conditions	Macroinvertebrate/Marine invertebrate	Algae distribution & Identification	Species Survey	Indicator Species	Behavioral Patterns	Micrometeorology (fluxes & Isotopes)	Sap Flow
Dam Operations:									
Which sediments will be mobilized under different dam operating conditions?									
How is aquatic habitat impacted by flow, temperature, water quality, and sediment movement?									
What role do intermittent disturbances play in the downstream ecosystem, and how is this impacted by the altered flow regime?									
How can we (re)engineer dams to facilitate migration of fish and to prevent recreational accidents?									

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Groundwater:									
What is the long-term ecological effect of upgradient groundwater pumping on riparian zones/wetlands?									
What are the temporal and spatial limits on groundwater withdrawals to minimize flow reduction?									
Effects of Climate Change:									
How will aquatic species respond to climate change-induced shifts in temperatures and low flow patterns?									
How can we improve predictions of flow rates with climate-induced changes to snowmelt patterns?									
How can we improve predictions of the impacts of interannual variability on geomorphology and ecology under a shift in temperature and precipitation patterns?									

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Water Quality:									
What will be the effect of shifting precipitation patterns on nutrient, oxygen, and temperature distributions in rivers at multiple scales?									
What are the cumulative effects of major changes in nutrient loads on riverine ecosystems?									
How can we improve the modeling of erosion, transport, and deposition of sediment in rivers?									
How do pharmaceuticals and other anthropogenic organic compounds affect ecosystems?									

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Appendix C

Biographical Sketches for Committee on River Science at the U.S. Geological Survey

Donald I. Siegel, *Chair,* is a professor of geology at Syracuse University, where he teaches graduate courses in hydrogeology and aqueous geochemistry. He holds B.S. and M.S. degrees in geology from the University of Rhode Island and Pennsylvania State University, respectively, and a Ph.D. in hydrogeology from the University of Minnesota. His research interests are in solute transport at both local and regional scales, wetland-ground water interaction, and paleohydrogeology. Dr. Siegel is a recipient of the O. E. Meinzer Award, presented by the Hydrogeology Division of the Geological Society of America (GSA). He recently served as a counselor of GSA, and is an associate editor of the *Hydrogeology Journal*. He has been a member of numerous NRC committees, including the Committee on Wetlands Characterization, Committee on Techniques for Assessing Ground Water Vulnerability, and Committee on Review of the USGS National Streamflow Information Program.

A. Allen Bradley, Jr. is an associate professor of civil and environmental engineering at the University of Iowa and a research engineer at IIHR Hydroscience & Engineering. His research interests are in the areas of hydrology and hydrometeorology, including flood and drought hydrology, hydroclimate forecasting, and water resource applications of remote sensing. He received his B.S. in civil engineering from Virginia Tech, an M.S. in civil engineering from Stanford University, and a Ph.D. in civil and environmental engineering from the University of Wisconsin.

Martha H. Conklin is a professor and founding faculty member at the School of Engineering of the University of California, Merced. She was formerly a professor in the Department of Hydrology and Water Resources at the University of Arizona. Her research interests include biogeochemistry, metal cycling, surface-water and shallow groundwater interactions, organic chemical distribution in soil and groundwater, and chemical processes in snow. She received her B.A. in physics from Mount Holyoke College and her M.S. and Ph.D. in environmental engineering science from the California Institute of Technology.

Clifford S. Crawford is a professor emeritus of biology at the University of New Mexico (UNM). He received a B.A. in biology from Whitman College, and M.S. and Ph.D. degrees in entomology from Washington State College. After three years on the biology faculty at Portland State College, he spent the rest of his career at UNM. Until the mid-1980s his research dealt mainly with the biology of terrestrial arthropods in arid and semiarid ecosystems. Since then, he has focused on the riparian ecology of those regions, with emphasis on the functioning and management of the Rio Grande river forest (bosque). He led an interagency team that wrote the "Middle Rio Grande Ecosystem: Bosque Biological Management Plan" in 1993. He is now the director of the Bosque Ecosystem Monitoring Program, which involves the public in tracking long-term environmental change along the middle Rio Grande.

Gerald E. Galloway is a research professor and professor of engineering at the Glen L. Martin Institute, University of Maryland, College Park. Before joining the University of Maryland, he was vice president of the Enterprise Engineering Group at the Titan Corporation in Arlington, Virginia. Dr. Galloway is a former secretary of the U.S. Section of the International Joint Commission. Dr. Galloway has served as a consultant on water resources engineering and management issues to the Executive Office of the President, the World Bank, the Organization of American States, the Tennessee Valley Authority, and the U.S. Army Corps of Engineers. Dr. Galloway is a former dean of the Academic Board (chief academic officer) of the U.S. Military Academy. Dr. Galloway holds M.S. degrees from Princeton, Penn State, and the U.S. Army Command and General Staff College. Dr. Galloway received his Ph.D. degree in geography from the University of North Carolina.

Marcelo H. Garcia is the Chester and Helen Siess Professor and director of the Ven Te Chow Hydrosystems Laboratory at the Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign. He is a leader in the field of river mechanics, sediment transport, sedimentation engineering, and environmental hydraulics. He is best known for his research in sediment entrainment from riverbeds, flow and transport in vegetated channels, the mechanics of oceanic turbidity currents, and the dynamics of mudflows in mountain areas. He is author of the book *Hydrodinamica Ambiental* (Environmental Hydrodynamics) and has served as editor of the *Journal of Hydraulic*

Research (IAHR) since 2001. He holds a Ing. Dipl. from the Universidad Nacional del Litoral, Argentina, in water resources and an M.S. and Ph.D. from the University of Minnesota, both in civil engineering.

Richard E. Howitt is professor of economics at the University of California, Davis. Dr. Howitt's research focuses on resource and environmental economics, quantitative methods, and econometrics. His interests include developing calibration methods based on maximum entropy estimators to model the economic structure of resource use from disaggregated physical data, including remote sensing methods, to infer the underlying economic functions. Much of his research has focused on California's water resources, including water markets in the San Joaquin Valley and the Westlands Water District. He has published in such areas as river water quality, water use, water management, and water institutions. Dr. Howitt received his Ph.D. and M.S. degrees in economics from the University of California, Davis.

Margaret A. Palmer is professor and director of the University of Maryland (UM) Center for Environmental Science, Chesapeake Biological Laboratory. She has also served as the director of the Ecology Program at the National Science Foundation (NSF), director of the Biological Sciences Program at UM, and visiting scientist at the Smithsonian Institution. Her activities and awards include Aldo Leopold Leadership fellow, Lilly fellow, AAAS fellow, Board of Trustees for the Chesapeake Bay Trust, Board of Advisers for the National Center for Earth Surface Dynamics, Board of Advisers for American Rivers, and Board of Advisers for the NSF Long Term Ecological Research Network. She studies a broad range of marine and freshwater ecological topics with a particular focus on restoration ecology and watershed science. Recent work includes research examining the link between biodiversity and ecological processes in freshwater ecosystems and the influence of global environmental change on biodiversity linkages between land and freshwater ecosystems. She has an undergraduate degree in biology from Emory University in Georgia and graduate degrees in oceanography from the University of South Carolina.

John Pitlick is an associate professor in the Geography Department, University of Colorado-Boulder, and Faculty Affiliate of the Environmental Studies Program. Dr. Pitlick's research interests are in the areas of surface-water hydrology and fluvial geomorphology. His research focuses on processes of sediment transport and channel change in both natural and altered river systems. The principal goal of this research is to develop process-based models coupling hydrology, sediment transport, and geomorphology across a continuum of scales. Additional research being done in collaboration with fisheries biologists and aquatic ecologists seeks a more detailed understanding of interactions between geomorphology and ecosystem processes, including food-web dynamics and nutrient cycling. In addition to field-based research, he has initiated laboratory studies to model stream-channel response to flood flows, and completed a hydrologic analysis of the effects of post-1950 changes in temperature and precipitation on the timing and volume of runoff in rivers throughout the western United States.

N. LeRoy Poff is an associate professor in the Biology Department of Colorado State University. Dr. Poff received a B.A. in biology from Hendrix College, an M.S. in environmental sciences from Indiana University in Bloomington, and a Ph.D. in biology from Colorado State University. His primary research interests are in stream and aquatic ecology and in quantifying the responses of riverine ecosystems to natural and altered hydrologic regimes, from local to watershed to regional scales. Dr. Poff has served as a member of the Adaptive Management Forum for CALFED river restoration projects, the Scientific Review Team for the King County (Seattle, Washington, Normative Flows Project, the Scientific and Technical Advisory Committee for American Rivers, and the Scientific Advisory Board of the David H. Smith Conservation Research Fellowship Program for The Nature Conservancy. He is also an Aldo Leopold leadership fellow of the Ecological Society of America.

Stuart S. Schwartz is senior research scientist at the Center for Urban Environmental Research and Education at the University of Maryland, Baltimore County. Before joining UMBC, Dr. Schwartz directed the Center for Environmental Science, Technology, and Policy at Cleveland State University, and served as associate director of the Water Resources Research Institute of the University of North Carolina. Dr. Schwartz served as an associate hydrologic engineer at the Hydrologic Research Center in San Diego, California, and directed the Section for Cooperative Water Supply Operations on the Potomac at the Interstate Commission on the Potomac River Basin. Dr. Schwartz's research and professional interests are in the application of probabilistic hydrologic forecasting and multiobjective decision making in risk-based water resources management, watershed management, and water supply systems operations. He received his B.S. and M.S. in biology and geology, respectively, from the University of Rochester and Ph.D. in systems analysis from the Johns Hopkins University.

David G. Tarboton is professor, Utah Water Research Laboratory and Department of Civil and Environmental Engineering, Utah State University, where he also serves as coordinator for the Utah State University Initiative. His research interests are in spatially distributed hydrologic modeling, applying digital elevation data and Geographic Information Systems in hydrology, stochastic hydrology using nonparametric techniques, snow hydrology, geomorphology, landform evolution and channel networks, and terrain stability mapping and stream sediment inputs. Dr. Tarboton received his B.S. in civil engineering from the University of Natal in Durban, South Africa, in 1981, and an M.S. and Sc.D. in civil engineering from the Massachusetts Institute of Technology in 1987 and 1990, respectively.

William W. Woessner is a Regent's Professor of Hydrogeology in the Geoscience Department of the University of Montana, Missoula, and acting director for the Center for Riverine Science and Stream Renaturalization. His research concentrates on quantifying flow systems in intermountain valleys, resource analysis, ground water and surface-water interactions, characterization of hazardous wastes and contaminant transport including virus transport, and the use of groundwater flow models to evaluate conceptual models and make predictions. He is coauthor of a widely used and widely translated text *Applied Groundwater Modeling*. He received his B.A. in geology from the College of Wooster, an M.S. in geology from the University of Florida, and an M.S. in water resources management and a Ph.D. in geology from the University of Wisconsin-Madison.