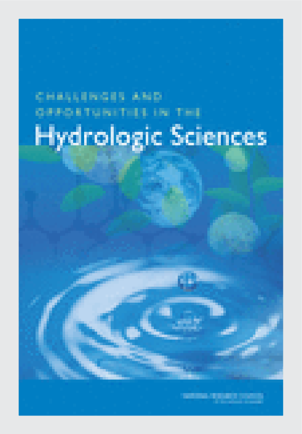

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CHALLENGES AND OPPORTUNITIES IN THE

Hydrologic Sciences

Committee on Challenges and Opportunities in the Hydrologic Sciences

Water Science and Technology Board

Division on Earth and Life Studies

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Preface

The publication of *Opportunities in the Hydrologic Sciences* in 1991 was a watershed event for the hydrologic sciences. This highly influential report of a National Research Council (NRC) committee, chaired by Peter S. Eagleson, Professor Emeritus, Massachusetts Institute of Technology, envisioned hydrologic science as a distinct geoscience and set forth a corresponding research agenda for the field.

Today, anyone who reads the "Blue Book," as the 1991 NRC report came to be affectionately known, must be struck by how the research agenda envisioned then still serves as a sturdy framework for the field and will undoubtedly do so for a long time in the future. Of course the hydrologic sciences have advanced and matured tremendously since 1991. Novel scientific studies now are possible because they can be built on successes of the past and can employ powerful new analytical, measurement, and computational technologies that have emerged over the past two decades and even over the past several years. There are completely new possibilities for learning how water shapes the surface of Earth (and other planets) and creates vegetation patterns, how the hydrology of the land surface both drives and is driven by atmospheric processes, how complex biogeochemical processes are intertwined with hydrological processes, and how a host of the research questions posed in the Blue Book now can be attacked advantageously. In addition to establishing the conceptual, empirical, and theoretical foundations of the science, refining and bolstering the fundamental base for hydrologic sciences is essential to support those who grapple with a multitude of water-related problems in a world that needs increasingly more energy, food, and water for humans while protecting ecosystem integrity, biodiversity, and irreplaceable landscapes, all in the face of a changing climate. Talk about challenges!

Recognizing the need to strengthen and adjust its hydrologic science research efforts, in 2009 the National Science Foundation (NSF) Earth Sciences leaders requested that the NRC's Water Science and Technology Board (WSTB) organize a study of current challenges and opportunities for the hydrologic sciences. The WSTB appointed a committee and charged it "to review the current status of hydrology and its subfields and the coupling with related geosciences and biosciences, and identify promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment." The members of the WSTB-appointed committee came from the field of hydrologic science and related biosciences and geosciences disciplines. The committee met with program managers from NSF and other federal agencies, heard the perspectives of a number of highly respected scientists and engineers in the field, held a "town hall" gathering at the American Geophysical Union Fall Meeting in 2009 to hear from the community, and solicited written input from members of the hydrologic and broader geosciences community. The committee read many previous reports and reviewed a great deal of literature and, in closed sessions, discussed and deliberated the future of the field and how to respond to the charge. This report is the result of that work. It is not, and was not meant to be, a comprehensive compendium of detailed research projects that might be undertaken in advancing hydrologic science, nor does it seek to define a field—a distinct geoscience—as did the Blue Book. Rather, it presents a high-level view of the field and gives broad examples of the "promising new opportunities to advance hydrologic sciences" as requested in the charge. It also outlines some of the challenges that face NSF, other agencies engaged in research in hydrologic sciences, and the hydrologic sciences community in fulfilling the vision for the field. The committee members are unanimous in the hope that the report will stimulate new research, some of which will undoubtedly extend beyond the specifics of what is written and into disciplines related to hydrologic sciences, but all of which will contribute to a shared vision of a vibrant and exciting hydrologic science of the future.

As the committee chair, I thank the members of the committee for their hard work in preparing this report, for their good-natured approach to reaching consensus on the many issues that we discussed, and for the wonderful camaraderie that they exhibited throughout our work together. This report, like all NRC reports, was made possible by excellent staff work. I thank Anita Hall for managing logistics for the committee. I especially want to thank Laura J. Helsabeck, the WSTB study director for the project, for her major contributions—both editorial and substantive—to the work, for keeping me focused on the tasks that needed to be accomplished, and for shepherding the report through the NRC publication process.

This report was reviewed in draft form by individuals chosen for their breadth of perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review was to provide candid and critical comments to assist the institution in ensuring that its published report is scientifically credible and that it meets NRC institutional standards for objectivity, evidence, and responsiveness to the study charge. The reviewer comments and draft manuscript remain confidential to protect the deliberative process. We thank the following reviewers for their helpful suggestions, all of which were considered and many of which were wholly or partly incorporated in the final report: Mary Anderson, University of Wisconsin-Madison; Susanne Anderson, University of Colorado, Boulder; Jean Bahr, University of Wisconsin-Madison; Victor Baker, University of Arizona; Susan Brantley, Pennsylvania State University; Stephen Burges, University of Washington; Yu-Ping Chin, The Ohio State University; Jeff Dozier, University of California, Santa Barbara; Howard Epstein, University of Virginia; Dennis Lettenmaier, University of Washington; Chris Paola, University of Minnesota; Donald Siegel, Syracuse University; Deborah Swackhamer, University of Minnesota, St. Paul; and Patricia Wiberg, University of Virginia.

Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Edwin Przybylowicz, Retired, Senior Vice President, Eastman Kodak Company. Appointed by the NRC, he 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 received full consideration. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

George M. Hornberger, *Chair*
Committee on Challenges and Opportunities
in the Hydrologic Sciences

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Summary

An abundance of liquid water sets Earth apart from almost every planetary body yet discovered in the galaxy. Water shapes the terrestrial surface of the planet and transports the resulting solutes and sediments from mountaintops to the ocean depths. Water is a crucial element of weather and the climate system. Water determines the form, life history strategies, and productivity of vegetation, ultimately controlling rates of photosynthesis in the biosphere. Water serves as habitat to an immense variety of aquatic species and as a necessary resource for all terrestrial species. Understanding the storage and movement of water through the biosphere is essential for understanding the physical structure, chemistry, biodiversity, and productivity of the biosphere. It is scant wonder that scientists who study Earth and its ecosystems are fascinated by fundamental questions about flows of water and attendant consequences.

Although water is renewable, it is not inexhaustible. Throughout history, civilizations have flourished with abundant water, accomplished engineering feats to secure its presence, and collapsed due to the lack thereof. Today, human influences on the environment are even greater than they were in the past and pose major challenges. Global population growth has led to increased demand for water to support agricultural, industrial, and drinking water needs, with water withdrawals that have become unsustainable in many parts of the world. Climate variability and change, land use change, and demographic change place varying stress on the planet's water resources. Access to safe water supplies remains a challenge in many parts of the world. As a result of reduced water supply and quality, the rates of species extinction are highest for freshwater organisms. At the core of the solutions associated with these complex challenges is hydrologic science.

Catalyzed in part by the 1991 National Research Council (NRC) report *Opportunities in the Hydrologic Sciences*, the field of hydrologic science (or "water science" or hydrology) has developed into a distinct Earth science discipline with the goal of understanding the movement of water at all scales and environments and its interaction with climate and life on Earth. This understanding is motivated as much by scientific curiosity as by the desire to address critical societal problems related to water and its impact on human welfare and the environment. Over the past 20 years, new scientific understanding has been enabled by unprecedented measurements and observations of hydrologic processes, made possible through technological and scientific advances in chemical analytical instrumentation, new sensor development, remote sensing and geophysical techniques, increased computation capabilities, and improved hydrologic modeling. Today, hydrologic science is a distinct and critical component of geosciences, linking the atmosphere, land, and oceans and contributing to understanding life on Earth. By its very nature, hydrologic science stands at the interdisciplinary interface with other geosciences, such as atmospheric, ecological, and biological sciences. As a result, new subdisciplines have emerged or old subdisciplines are maturing that advance the frontiers of interdisciplinary research, e.g., hydroclimatology, hydrometeorology, geobiology, hydroecology, hydrogeomorphology, ecogeomorphology, and Earth-surface dynamics. Hydrologic science is central to all of these fields and, therefore, is becoming itself redefined and enriched.

The National Science Foundation (NSF) requested that the NRC (1) review the current status of hydrologic science and its subfields and the coupling with related geosciences and biosciences, and (2) identify promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment (Box S-1).

In response, the NRC formed the Committee on Challenges and Opportunities in the Hydrologic Sciences, which authored this report. The report is written for the members of the hydrologic community, mainly the research community, which includes not only academics but also scientists and engineers from the private sector, federal agencies (most notably the Hydrologic Science program and other Earth Science programs within NSF, when appropriate), decision makers interested in water research and policy, and those with Earth sciences and water resource-related missions interested in where hydrologic science fits into the surface-earth sciences. The report is also written for graduate and undergraduate students seeking inspiration, general knowledge of the field, or guidance when selecting a focus within the field. Although the primary audience is the hydrologic

BOX S-1
Statement of Task

This study will identify the challenges and opportunities in the hydrologic sciences, including (1) a review of the current status of the hydrology and its subfields and of their coupling with related geosciences and biosciences, and (2) the identification of promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment. The goal is to target new research directions that utilize the capabilities of new technologies and not to critique existing programs at NSF or elsewhere. The resulting report will not make budgetary recommendations.

Specifically, the study will:

- Identify important and emerging issues in hydrology and related sciences,
- Assess how current research modalities impact the ability of hydrologic sciences to address important and emerging issues,
- Identify needs and research and education opportunities for making significant advances in hydrologic sciences, and
- Assess current capabilities in and identify opportunities to strengthen observational systems, data management, modeling capacity, and collaborations needed to support continued advancement of hydrologic sciences, and also their relationships to and value for mission-related agencies and, reciprocally, how observational systems of mission-related agencies relate to and contribute to hydrologic sciences.

community, the water-related challenges and opportunities presented in the report are complex and broad. Thus, the report reaches out to other disciplines by articulating opportunities for important contribution in collaborations with hydrologic scientists and engineers.

The signature of a scientific challenge is that it is compelling, both in the domain of intellectual curiosity as well as in the domain of consequence for human welfare. Embedded within the water-related issues facing the planet are many such scientific challenges. How does knowledge about the hydrologic past prepare us for the future? Does the planet face shrinking ice and growing deserts? How are bioclimatic zones evolving? Can sufficient clean water be supplied where and when humans and natural ecosystems need it? How much water does an ecosystem need? Can water quality be assessed and managed to protect human and ecosystem health?

The committee identified three major areas that define the key scientific challenges for the hydrologic sciences in the coming decade: The Water Cycle: An Agent of Change, Water and Life, and Clean Water for People and Ecosystems. For each major area, the committee enumerates some of the most challenging concepts and identifies research opportunities for attaining progress in the field; the main message of each is represented in boldface, below. Hydrologic science in the 21st century is a very broad field that encompasses all of traditional hydrologic science as defined in *Opportunities in the Hydrologic Sciences* and extends into areas that have traditionally been of interest to other disciplines and related subdisciplines. As such, the field is tasked with integrating and collaborating with related sciences and embracing work in other disciplines and subdisciplines. The report covers physical-hydrological sciences, including physical hydrology, geomorphology, paleohydrology, and climate science; biological-hydrological sciences, including ecohydrology, aquatic ecology, biogeochemistry, soil science, and limnology; and chemical-hydrological sciences, including chemical hydrology, and aquatic geochemistry. The three major areas overlap, reflecting the complex and intertwined water-related challenges facing the hydrologic community and other geosciences. All three major areas present a blend of equally important "curiosity-driven" and "problem-driven" research.

Opportunities in the Hydrologic Sciences cemented the foundation of the field. This report builds on that foundation by stressing not only further building of the field, but also the broader interdisciplinary potential of a science with an established foundation. It is not possible to capture all of the scientific details contained in the report's chapters in this summary; those interested in additional synopses may find the concluding sections of each chapter particularly interesting.

THE WATER CYCLE: AN AGENT OF CHANGE

Water is a dynamic agent whose influence is central to processes that produced the world as we know it and that will affect its evolution into the future. Moreover, human intervention in the water cycle alters water's dynamic role on the planet. All the phases and states of the water cycle are linked, and impacts of human activities on one aspect of the hydrologic cycle are consequently transferred to other components. Understanding the physical role of water in the past, present, and future of Earth's system has been the backbone of the field of hydrologic science since its inception. Progress has been made; yet it is this progress that has highlighted important gaps of knowledge and has defined challenging new research opportunities in understanding water-cycle dynamics in a changing environment. These challenges span a range of topics related to not only physical hydrology but also other related disciplines and subdisciplines such as geomorphology, paleohydrology, and climatology.

The hydrologic cycle is being altered or "replumbed" through a variety of competing and escalating human activities, such as agriculture, infrastructure development, and the "water energy nexus."[1] Climate change is also altering the hydrologic cycle. For example, the global increase in precipitation and changes in surface water flow and therefore the hydrology of the land surface, which in turn alters the climate through, for example, changes in evapotranspiration processes. Human activity is now a significant and recognizable component of the water cycle, a conclusion in keeping with the argument that the planet is moving into a new geologic epoch called the "Anthropocene."[2] This planetary replumbing has and will continue to impact water availability and distribution. **A challenge for the hydrologic community is to understand replumbing; for example, the downstream consequences of urban growth or changes in the severity, duration, and occurrence of floods and droughts as a result of climate change, and to apply this understanding to making predictions for the future.**

Hydrologic fluxes interconnect the water, energy, and biogeochemical cycles and are conditioned by human impacts on the water cycle. Fundamental gaps exist in the understanding of the climatology and the average spatial and temporal characteristics of key hydrologic fluxes, namely, evapotranspiration and groundwater fluxes over large regions. **Furthering understanding of the processes that link components of the water cycle is no less important than understanding the human impacts on the water cycle.** This requires direct information on the patterns and dynamics of evapotranspiration and groundwater fluxes. Remote sensing measurements, ground-based measurements, and modeling are key tools in developing this understanding.

The processes that define water fluxes occur at multiple scales, for example, turbulent gusts of wind, large weather systems, the first drops of water that initiate streams, and the complex system of rivers that define drainage basins. The past few decades have witnessed not only major advances in understanding and modeling the space-time variability of hydrologic processes including precipitation, soil moisture, and streamflow, but also, more importantly, development of conceptual frameworks to describe this variability across a wide range of scales—following a physical, phenomenological, or statistical perspective—known as scaling theories. Because observations cannot be made all the time and everywhere in a watershed and that physically based distributed hydrologic models require extensive data for calibration and verification, such scaling theories are not only of theoretical interest but also of immense practical importance.

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[1] The "water energy nexus" is the link between the human need for water (the delivery of which requires energy) and the human need for energy (the production of which requires water).

[2] Crutzen, P. J. 2002. Geology of mankind. Nature 415:23; Vince, G. 2011. An epoch debate. Science 334:32-37.

Challenges remain in certain areas, including comprehending how processes at the small scale (hillslope) interact with those at larger scales (organized river networks) to define the hydrologic response. **Because interactions at overlapping scales change hydrologic patterns in subtle ways, disentangling the causality of subtle shifts and regime changes in streamflow and understanding their environmental impact is a challenge.**

The climate system can vary at long time scales driven by slowly varying conditions in the world's oceans and cryosphere as well as rapidly shift into new modes of behavior that are different from the historical experience. Both can result in significant hydrologic changes. **Understanding the hydrologic response to abrupt climate change[3] over short time scales and to slowly varying natural climate change is far from complete.** This understanding is critical for comprehensive scenarios of future hydrologic variability (e.g., runoff and recharge). Paleoclimatic records can inform the development of a plausible range of hydrologic conditions under natural climate variability.

The presence of water in and on planets changes everything—from deep interior dynamics to the surface evolution of landscapes and to the potential for life. Therefore, when exploring other planets, a key goal is to quantify the abundance and dynamics of water and other fluids, not only to determine the possibility of life elsewhere but also to understand how the entire planet operates. **The study of hydrologic processes on other planets defines the new field of "exohydrology," and research in this area is only just beginning.** The experience, insights, observational methods, and models developed by hydrologic scientists are needed to decipher the climate history of other planets. The fluids may be different (e.g., liquid hydrocarbons on Titan), but the processes of precipitation, surface runoff, and subsurface flow can still occur. Although this study is necessary to understand the evolution of other planets, it also tests the scientific understanding of how Earth works.

WATER AND LIFE

Water and life are inseparable and interacting. The evolution of life on Earth likely began with the formation of liquid water and has been shaped by the flow of water ever since. Water is essential for all living organisms and, on land, the timing of water delivery and the magnitude of water supply structures biological systems at all spatial and temporal scales. Over

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[3] The committee adopts a generally agreed upon definition of "abrupt" change: "A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruption in human and natural systems" (U.S. CCSP, Synthesis and Assessment Product 3.4, 2008).

geologic time scales, hydrologic change has been a major force of natural selection. Across modern Earth, annual precipitation and temperature explain much of the variation in the stature and composition of vegetation, and the pattern of hydrologic connections constrains the distribution of many organisms as they migrate to complete their life cycles. Ecologists and aquatic ecologists, geomorphologists, soil scientists, and hydrologic scientists have found a common research frontier at the nexus of water and life.

Despite limited signature of the early history of the Earth on the geologic record, it is clear that life was interacting with the physical system. Landscapes, hydrologic processes, ecosystems, and climate have co-evolved throughout Earth's history and across all spatial scales. Furthermore, the relative importance and rates of these processes have changed dramatically throughout Earth's history. For example, for 4 billion years, land plants did not exist; all of the various ways that plants currently influence water distribution (e.g., flux rates) between the land and atmosphere were absent. The evolution of land plants radically changed the Earth's hydrologic system. **The past, with radically different biota, topography, and atmospheric and ocean chemistry, presents an opportunity for hydrologists to explore how key processes in the hydrologic cycle differed, and how these processes contributed to Earth's evolution.**

Hydrology plays a critical role in driving the terrestrial ecosystem patterns that exist and evolve on the Earth. Conversely, vegetation responds to and controls local and regional hydrology. For example, in arid and semi-arid climates, water limitation is a major determinant of vegetation patterns. In such environments, plants themselves may create spatially variable conditions favorable to their survival by influencing soil characteristics that determine surface water infiltration, moisture retention, and erosion. **Many challenging research questions arise when exploring how topography, vegetation (and their animal ecosystems), and the hydrologic processes that connect them may co-organize over geomorphic time scales.**

The estimates vary, but there is general agreement that more life is below Earth's surface than above it. Furthermore, the diversity of this subsurface life is staggering; just a few grams of soil could contain thousands of species. Life extends well below the soil layer, as well, into the weathered rock zone and even the bedrock. Subsurface ecosystems form their own environments, create and direct hydrologic pathways, release gases to the atmosphere, and control access to moisture and nutrients to aboveground ecosystems. **How subsurface biota are controlled by and yet also influence hydrologic processes is a frontier area of research.**

Changes in flow regimes alter not only the spatial extent and quality of freshwater habitats, but also the connectivity between freshwater ecosystems. As habitat quality and quantity declines and freshwater systems become increasingly fragmented, aquatic and floodplain species are lost and the water quality of the world's rivers and coastal zones is degraded. In other words, hydrologic flow regimes and aquatic ecosystems are linked, resulting in a co-evolution of rivers and river ecosystems. **An important challenge for the hydrologic and ecological communities is to understand the complex ways in which flow regimes impact critical ecological processes and the maintenance and dispersal of aquatic taxa in aquatic ecosystems.**

Earth's ecosystems are in a state of transition as a result of climate variability and change and changing land use. **The processes that determine transitions in ecosystems are not well characterized or understood; yet the viability of ecosystems as localized communities and as part of the global co-evolution of water and life depends critically on these transitions.** The response of the sensitive extremes of Earth's hydroecosystem, that is, cold regions and warm deserts, to human-induced change is expected to be complex. Low flow in fluvial networks also deserves attention. Specifically, the spatial extent of streamflow in channel networks during low flow periods is unknown, yet it defines the aquatic ecosystem and the availability of surface water to terrestrial biota, and is especially vulnerable to the effects of land use and climate change.

A fundamental shift has taken place in how society values natural processes and manages landscapes. Wetlands, once considered low-quality land in need of drainage, are known to provide a wide range of critical ecosystem services, from flood attenuation to providing essential habitat for commercially important species. Rivers, viewed mainly as large-scale canals, were blocked from migration, cut off from their floodplains, and depleted of sediment and water. Now efforts are under way to restore natural processes to rivers, in order to regain aquatic ecosystems functions and flood management. Management actions for a desired outcome, whether it is changing grazing practices or adding wood to streams, are based on predictions (by inference, experience, or more quantitative approaches). **Scientists currently lack both sufficient understanding from field studies and quantitative models to make reliable predictions about desired outcomes from water management decisions in many applications.**

CLEAN WATER FOR PEOPLE AND ECOSYSTEMS

Most living things depend on availability of clean water. The quality of the planet's waters is changing on time scales of minutes to centuries in ways that are only partially understood. Ensuring clean water for the future requires an ability to understand, predict, and manage changes in water quality. Science is needed to ensure the knowledge base necessary to address the challenges of maintaining good water quality where it exists and restoring it where it has been degraded. Recent advances in chemical analytical techniques have enabled detection of minute amounts of contaminants in water. The committee anticipates a surge of new knowledge from hydrologic scientists and engineers, aquatic geochemists, and others in related disciplines to advance the scientific understanding needed to promote clean water for the planet.

Geological materials and surfaces are enormously complex, which confound the description of fundamentally important hydrologic processes. Earth's heterogeneity can be observed at different scales from pore size in the subsurface, to the irregularity of a river channel, to patchiness of ecosystems—all of which influence water flow and, in turn, the movement and concentration of constituents. Furthermore, heterogeneity influences how landscapes are connected through water mediated transport. **A challenge exists in developing basic hydrologic principles and tools to further understand the movement of contaminants through an irregular and interconnected world.** This applies to both the surface (how river networks interact with channels and upland areas) and the subsurface (the role of heterogeneity and connectivity in subsurface transport).

The discharge of contaminants has disturbed Earth's water chemical composition and begs the question: how widespread and severe is the deterioration in the planet's water quality? The idea that clean water is accessed only upstream from human activity has hardly ever proven to be a useful concept and now is particularly questionable given that "there is no upstream anymore." Some contaminants have spread globally through the water cycle. Even after years of concern about a variety of contaminants, some problems are worsening and this trend is expected to continue in the future. The water quality profile of the planet is evolving in space and time as new contaminants are introduced to the water cycle and old contaminant use continues. Understanding of this evolution has significantly advanced in recent years, largely because gains in chemical analytical instrumentation have enabled detection of synthetic organic contaminants in water. Much of the fundamental work needed to understand the heterogeneity and connectivity mentioned above is critical to further understanding of this evolution. **A research challenge exists in promoting the understanding of how contaminants interact with hydrologic processes and, in turn, impact stream ecosystems.**

The final layer of complexity in the water quality picture involves the large-scale drivers of water quality. As Earth's human population grows toward 9 billion,[4] as resource use intensifies, and as climate changes, the maintenance of adequate water quality will rely on new knowledge. **The hydrologic research community has an obligation to tackle the water quality issues embedded within large-scale drivers of water quality.** Specifically,

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[4] The United Nation's *World Population Prospectus: The 2010 Revision*, available online: http://esa.un.org/unpd/wpp/index.htm.

Challenges and Opportunities in the Hydrologic Sciences, at a Glance

The committee identified three major areas that define the exciting challenges and opportunities in hydrologic science today: The Water Cycle: An Agent of Change, Water and Life, and Clean Water for People and Ecosystems. Examples of research opportunities in each of these areas are presented in Chapters 2, 3, and 4 of the report with supporting information, are summarized in boldface in the Summary (text above) and in Chapter 5, and are listed here in abbreviated form. The numbering below (2.1, 2.2, etc.) corresponds to the location of each section in the report.

Research opportunities to better understand the water cycle include understanding:

2.1 The change in hydrologic fluxes as a result of planetary replumbing;

2.2 The processes linking components of the hydrologic cycle, namely, evapotranspiration and recharge;

2.3 The causality of subtle shifts and regime changes in streamflow and the environmental impact of these changes;

2.4 The hydrologic response to abrupt changes in climate and land cover over short time scales and this response in the context of multidecadal to millennial and longer variations in climate; and

2.5 The hydrologic processes on other planets ("exohydrology").

Research opportunities at the nexus between water and life include understanding:

3.1 How key hydrologic processes affect the co-evolution of life and the planet;

3.2 How topography, terrestrial and aquatic ecosystems, and the hydrologic processes that connect them may co-organize over geomorphic time scales;

3.3 How subsurface biota are controlled by and influence hydrologic processes;

3.4 The complex ways in which flow regimes impact critical ecological processes and the maintenance and dispersal of aquatic taxa in aquatic ecosystems;

3.5 The processes that determine transitions in ecosystems; and

3.6 Hydroecologic outcomes from conservation and restoration management decisions.

Research opportunities related to providing clean water for people and ecosystems include understanding:

4.1 The movement of contaminants through an irregular and interconnected world;

4.2 How contaminants interact with hydrologic processes and, in turn, impact stream ecosystems; and

4.3 The impact on water quality of large-scale drivers such as climate change, the water energy nexus, agriculture, and urbanization.

hydrologic scientists need to probe the geochemical phenomena associated with changing urban flow paths. Exploring the numerous ways that climate change can produce new regimes that impact water quality (i.e., increasing sediment, chemical, and pathogen loading in runoff; saltwater intrusion threatening the quality of coastal groundwater supplies; changes in the thermal regime of water bodies) is also critical. Changes in flow regime and, in turn, in water quality as a result of agriculture is an area ripe for study in the interest of prompting sustainable practices.

A PATH FORWARD

Opportunities in hydrologic science have never been greater, and the challenges that lie ahead have never been more compelling. Fundamental new drivers of hydrologic science in the 21st century rest on the realization that: (a) humans are a dominant influence on water sustainability both at the global and local scales, (b) the world is becoming exceedingly "flat"[5] with respect to not only rapid dissemination of scientific knowledge but also learning from environments undergoing rapid change (e.g., deforestation, drought, agricultural expansion, etc.) and predicting future water scenarios in other parts of the world, and (c) the natural world is a highly nonlinear system of interacting parts at multiple scales prone to abrupt changes, tipping points, and surprises more often than previously thought possible. *What do these realizations mean for the future of hydrologic science?*

The committee concluded that some broad approaches will facilitate the conduct of the research outlined in this report:

- Interdisciplinarity: There is a need for interdisciplinary hydrologic research that takes advantage of cutting-edge technologies to grapple with the complex water-related challenges of today and tomorrow. As technology to probe Earth's mysteries advances, computer models become more and more sophisticated, research relies on ever more extensive data for modeling and analysis, and no single discipline provides the entire knowledge base; building mechanisms to share knowledge, equipment, models, data, and science requires a fostering platform and relevant resources.
- Range of Modalities[6]: A range of modalities plays a critical role in

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[5] The term "flat," coined by the author Thomas Friedman in his books *The World is Flat* (2005) and *Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America* (2008), is used to describe a new era of globalization allowing people and entities around the world to compete, connect, and collaborate.

[6] The committee interprets the term "modalities" in the statement of task as referring to capabilities within NSF and other federal agencies used to advance hydrologic research including contracts and research grants, instrumentation and facilities, and so forth.

hydrologic sciences that is key to tackling the challenges and opportunities in this report.

- Education: To successfully solve today's complex water problems, scientists, engineers, and water managers need disciplinary depth and intellectual breadth to bridge disciplines and the ability to effectively communicate science to policy makers.
- Translational Science: Multiway interactions among scientists, engineers, water managers, and decision makers (termed "translational hydrologic science") are needed to more closely connect science and decision making in order to address increasingly urgent water policy issues.

The committee elaborates on these points with advice, in boldface, below.

The charge to the committee is not specific to NSF. Although NSF (and, in particular its Hydrologic Science (HS) program) will play a critical role in hydrologic science research, other agencies and organizations also support hydrologic science and offer various modalities to advance hydrologic research. Therefore, the following advice applies in varying degrees to other agencies and programs in addition to NSF.

Research grants and contracts to individual Principal Investigators (PIs) come from a variety of federal, state, and local agencies as well as from private sources. An important part of this broad support package is NSF's HS program, which enjoys an expanding and vibrant talent pool, as reflected by a high proposal submission rate. **Hydrologic science is well served by the HS program's support of standard grants. This core research capability will continue to be important as NSF addresses the opportunities and challenges described in this report. As other agencies and organizations approach the challenges described in this report, their support of individual PIs also will be important.**

Along with single PI research, larger interdisciplinary groups and community capacity building has to be envisioned with an eye toward the future to tackle interdisciplinary science questions. All efforts should work in harmony rather than in competition to ensure a culture of sharing and growing within a curiosity-driven research environment for the benefit of society. **Collaborative, community building efforts will continue to be relevant for the multiple agencies and organizations that support hydrologic science, including NSF in general and the HS program in particular, in responding effectively to many of the opportunities and challenges presented in this report.** Numerous federal agencies and international organizations have varying degrees of responsibility in water science or water management. NSF-supported research and the programs of other agencies can be mutually beneficial. **Expansion of cross-agency programs and exploration of novel mechanisms of cross-agency partnerships, including opportunities**

to make use of observational programs and facilities, are likely prerequisites for effective response to the research goals suggested in this report.

The solution to the complex water-related challenges facing society today begins with education. Education of both graduate and undergraduate students in hydrologic science has gained ground in the last 20 years with the formation of new hydrology-related programs, degrees, and other educational efforts. Hydrologic and other sciences have benefitted from NSF's broad and deep experience in programs to support graduate students. **Continued NSF support of various educational modalities will enable beneficiaries to fulfill the research goals described in this report.** In light of the increasing need to support interdisciplinary research, the committee envisions educating scientists and engineers in both traditional programs and in nontraditional ways. **To tackle the complex issues outlined in this report, those who guide the next generation of hydrologic scientists and engineers should consider how to best prepare them for a scientific arena that differs from the norm.** By this the committee means an arena that spans a range of disciplines and offers a menu of new technologies to assist in tackling the challenges. It is important to cultivate hydrologic scientists and engineers with intellectual breadth and disciplinary depth and graduates with enriched communication skills to enable them to easily work on interdisciplinary teams. During the educational experience, periods of practical experience using the laboratory and field, exposure to new technologies, and service-minded activities ("hydrophilanthropy") are all techniques to achieve this goal.

The important and emerging areas set forth in this report focus on improving the knowledge of physical, chemical, and biological processes relevant to the hydrologic sciences. But improved knowledge of these processes doesn't necessarily translate to solutions and better management of water resources. Multiway interactions between scientists, engineers, water management, and decision makers will better connect science and decision making. This "translational hydrologic science" considers social, institutional, economic, legal, and political constraints. But what would translational hydrologic science look like in practice? Research agendas would be collaboratively produced by scientists, engineers, decision makers, and stakeholders. Engagements would be interactive (multiway), sustained, with feedbacks and iterations, and involve a time commitment from all parties. Translational hydrologic science clearly requires broadly interdisciplinary projects that are place-based and that include physical, chemical, biological, and social scientists as well as local stakeholders. An evaluation process that considers a project's multidisciplinary contributions (rather than narrowly focused research questions) is critical to successfully proposing, initiating, and executing translational research. **The committee encourages agencies and organizations to support an interpretation of solicitations on**

interdisciplinary hydrologic science that allows fair consideration of the new research directions in translational hydrologic science that are needed to solve societal problems. Underpinning success in translational hydrology is successful communication between involved groups. Yet communication can often be challenging because of factors such as the lack of a common vocabulary or a common understanding of terms. **The educational experiences for young hydrologic scientists should include experiences that enhance communication skills.**

This report challenges scholars in the hydrologic sciences to engage in disciplinary and interdisciplinary research that is both relevant and exciting and that continues to promote education to ensure that a new generation of hydrologic scientists and engineers equipped to face future water resource challenges is born. Water problems will become more complex and global water scarcity will continue to manifest itself in different ways, presenting challenges that have not heretofore been addressed in any consistent way. The challenges of the future, therefore, will require more systematic attention to the importance of hydrologic science in the public policy process. In turn, researchers in the hydrologic sciences will be required to collaborate and communicate with colleagues in the social sciences, including economics, political science, psychology, and sociology, to a far greater extent than has been the case in the past. Hydrologic science will thrive to the extent that it promotes this breadth simultaneously with deeper disciplinary knowledge.

1

The Hydrologic Sciences

The abundance of liquid water sets Earth apart from almost every planetary body yet discovered in the galaxy. The hydrologic cycle, or the movement of water through evaporation, atmospheric transport, precipitation, and river and groundwater flows, shapes the terrestrial surface of the planet and transports the resulting solutes and sediments from mountaintops to the ocean depths. Water supply and temperature together determine the form, life history strategies, and productivity of vegetation, ultimately controlling rates of photosynthesis in the biosphere. Liquid water serves as habitat to an immense variety of aquatic species and as a necessary resource for all terrestrial species. Understanding the storage and movement of water through the biosphere is essential for understanding the physical structure, chemistry, biodiversity, and productivity of the biosphere.

Although water is renewable, it is not inexhaustible. Throughout history, civilizations and ecosystems have flourished with the presence of water, executed engineering feats to secure its presence, and collapsed due to the lack thereof. Today, human influences are even greater, dominating the natural cycle of freshwater and causing environmental changes that are argued to have moved the planet into a new geologic period termed the "Anthropocene" (Crutzen, 2002; Vince, 2011). Global population growth has led to increased demand for water to support agricultural, industrial, and drinking water needs, with water withdrawals outstripping water supply in many parts of the world. Climate variability and change, land use change, and demographic change place varying stress on the planet's water resources. Access to safe water supplies remains a challenge in many parts of the world. The rates of species extinction are highest for freshwater organisms because of habitat destruction, changes in water quantity, and water quality degradation and the introduction of foreign species looms large (Dudgeon et al., 2006). The risk of future extinction of freshwater biota is projected to be five times higher than that of terrestrial biota and two times higher than that of coastal mammals (Ricciardi and Rasmussen, 1999). At the core of these challenges is hydrologic science.

WHAT IS HYDROLOGIC SCIENCE?

Hydrologic science or hydrology is, at its most basic level, the "science of water" that embraces topics from research on fundamental processes through operations associated with flood protection, drinking water supply, irrigation, and water contamination. The National Research Council (NRC) report *Opportunities in the Hydrologic Sciences*, known as the "Blue Book," defined hydrologic science as a distinct geoscience—"a geoscience interactive on a wide range of space and time scales with the ocean, atmospheric, and solid earth sciences as well as with plant and animal sciences." However, hydrologic science is also firmly anchored by phenomena that have direct and important relationships with the well-being of humans and natural systems. In fact, as noted by Thomas Dunne, hydrologic science:

> will remain vital only if (1) it discovers new phenomena, processes, or relationships governing the behavior of water and its constituents and (2) it focuses on real hydrologic phenomena, such as floods, droughts, drainage basins, material storages and fluxes, and even large-scale engineering effects such as streamflow modification, soil conservation, or channel modifications (NRC, 1998).

Hydrologic scientists are driven in their research by curiosity about how the natural environment functions. How water shapes landscapes is intimately interrelated with life on land as well as in water bodies and is a primary ingredient in the planet's climate engine. Some of the curiosity, however, arises directly from a desire to solve problems associated with a variety of hydrologic phenomena, as suggested by Dunne. This blend of "curiosity-driven" and "problem-driven" research in hydrologic science is one of the aspects that makes the field so vibrant and exciting and represents a defining feature of the future challenges and opportunities for the field.

> "[Water is the] elixir of life, the climatic thermostat and the global heat exchanger."
>
> *Opportunities in the Hydrologic Sciences,* NRC, 1991

Hydrologic science's origins lie deep within the engineering applications community. Greeks and Romans, who were pioneering hydraulic engineers, built aqueducts. Herodotus, Plato, Aristotle, and Hippocrates theorized about the hydrologic cycle, and this understanding was advanced in the Renaissance and the years following. Yet it was because of water's role in human affairs, primarily its availability and avoiding hazards, that the evolution of the science of hydrology followed the leadership of civil and agricultural engineers. During the 17th, 18th, and a large part of the 19th centuries the scale of hydraulic engineering efforts was modest yet, in the United States, dominated by engineers concerned with water supply and sanitation.

The evolution of hydrologic sciences in the United States throughout the late 19th century and the 20th century was one of ever expanding scope largely driven by societal needs. In 1879, the United States established itself as the primary supporter of water research by forming the U.S. Geological Survey, which has contributed major advances in areas such as sediment transport in streams and rivers, groundwater, and water chemistry since that time. At the turn of the 20th century, hydrologic science was introduced into U.S. universities. This introduction was largely in departments of civil engineering with a focus on floods, surface runoff, water supply, soil-plant-water relationships, agriculture, and groundwater but also within geography departments focusing on river and streamflow and other surface-water processes related to geomorphology. Subsequent teaching and research on hydrologic processes was introduced into agriculture and forestry departments, largely focusing on soil-plant-water relationships, and geosciences departments, largely focusing on groundwater. In 1930 the Hydrology Section of the American Geophysical Union (AGU) was created. By the mid-1900s research focused on various aspects of the hydrologic cycle and was being conducted in government and university labs throughout the United States.

In 1991—some 20 years ago—the NRC released the aforementioned report *Opportunities in the Hydrologic Sciences*, which was a thoughtful reflection upon the field of hydrologic science. The "Blue Book" envisioned hydrologic science as a distinct geoscience and set forth a corresponding research agenda for the field. In the years following its publication, the document stimulated discussion and various actions, which culminated in the widespread recognition of hydrologic science as a separate field within the Earth Sciences. These actions included strengthening of existing university programs and establishing new ones, as well as establishing the Hydrologic Sciences Program within the National Science Foundation's (NSF's) Directorate of Geosciences. The "science of water" was recognized as a critical component of geosciences linking the atmosphere, land, and oceans and contributing to the understanding of life on Earth.

The hydrologic community took on a separate identity as scientific hydrologists[1] and those in the community were and are proud to call themselves such. Hydrologic science developed into a discipline with a number of interrelated subdisciplines, some of which were created and active before the Blue Book's publication. These subdisciplines can be roughly categorized as pertaining to either the subsurface or the surface, despite the great deal of overlap in processes and interactions between the two and related research. An example of the former is groundwater hydrology, which deals with the movement of water in the upper layers of Earth's surface, compared to catchment hydrology, which is the study of surface water fluxes, particularly runoff, and transport of substances within a catchment or hydrologic basin.

The NRC formed the Committee on Hydrologic Sciences (COHS) in 1998 to provide a mechanism for continued promotion, integration, and advancement of hydrologic science at the interface with other related sciences. The COHS has produced and organized several reports, such as *Integrating Multiscale Observations of U.S. Waters* (NRC, 2008) and *Global Change and Extreme Hydrology: Testing Conventional Wisdom* (NRC, 2011). Other entities have issued visionary manuscripts to promote the field. For example, the Royal Netherlands Academy of Arts and Science published a forward-looking agenda in hydrologic sciences for its country and the globe (Royal Netherlands Academy of Arts and Sciences, 2005). The "Chinese Blue Book" took a holistic view of groundwater science in China and recommended priority research areas and strategies for advancing groundwater research and education (Zheng et al., 2009). Membership in AGU's Hydrology Section has more than doubled since 1998 (A. Orr, personal communication, May 19, 2010). Today it is acknowledged that a successful and distinct science has evolved, and much fundamental progress has been made (Box 1-1).

TECHNOLOGICAL AND SCIENTIFIC ADVANCES

Over the past few decades and accelerating in time, leaps in technology have enabled unprecedented measurement, observation, and fundamental advances in the conceptual understanding of hydrologic processes. Just comparing the technological capabilities available in 1991 to those available today attests to near-term opportunities available to realize the scientific vision and test the scientific hypotheses set forth in the original Blue Book and advanced in the following chapters. The Blue Book stated:

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[1] Here and throughout the report the term "scientific hydrologists" includes hydrologists, engineers, and those in related disciplines and subdisciplines participating in hydrologic research.

BOX 1-1
Water in Geosciences: Celebrating the Past and Looking Ahead, a Special Session at the 2009 AGU Fall Meeting

A special session was held at the 2009 AGU Fall Meeting titled "Progress in Hydrologic Sciences since the Blue Book" with the aim of taking a look at the scientific developments in hydrologic sciences since the Blue Book was published and to discuss perspectives for the open problems that lie ahead. The session was organized in honor of the founding Director of NSF's Hydrologic Science program (L. Douglas James) on his retirement after 17 years of leadership and dedicated service to the hydrologic science community. The presentations in this special session provided a perspective of the past accomplishments in hydrologic science with an eye toward the future. The session opened with remarks by Peter S. Eagleson, Professor Emeritus, Massachusetts Institute of Technology, who chaired the 1991 NRC Blue Book committee, on the origins of the Blue Book and his perspectives on where future opportunities lie. The talks that followed emphasized the vitality of hydrologic science at its disciplinary core as well as at the boundaries with atmospheric sciences, biogeochemistry, geomorphology, social sciences, and engineering. The talks also presented major breakthroughs in land-atmosphere interactions such as the effect of deforestation on hydrometeorological predictions, advances in generalized scaling theories of floods, the value of remote sensing data of precipitation, vegetation, and soil moisture in improving hydrologic modeling and prediction, new methodologies for characterizing hydrologic uncertainty, advances in data assimilation, advances in coupling geochemical and surface-groundwater systems, the role of social sciences in hydrologic prediction, and the need to translate increased scientific understanding into better management of water resources systems. The talks also presented a worldview perspective of water and international efforts in hydrologic science and practice, a renewed educational agenda for hydrologic science at the interfaces of geosciences using community collaboration, and the use of high-performance computing capable of resolving processes at scales of the order of meters in advancing hydrologic predictions in an Earth systems perspective. The need for changing perspectives to engage interdisciplinary synthesis and data-driven exploration to develop predictive models that can function in a changing environment was noted.

"In the history of the hydrologic sciences as in other sciences, most of the significant advances have resulted from new measurements." This remains as true today as when it was originally stated in 1991 although since then there have been game-changing innovations in measurement technologies. Many instruments are now deployed with remarkable pervasiveness and exchange data wirelessly with little to no latency. Devices are available to detect chemical and biological constituents with remarkable sensitivity. Taken together, hydrologic science is poised to advance in leaps and bounds enabled by the new measurements and the insights they afford.

Paired with or perhaps as a result of these game-changing innovations is a change in the context of how hydrologic science is done. Human impacts and inputs now represent a major wellspring of research questions and directions in the hydrologic sciences. The recognition of human-driven climate change has challenged hydrologic scientists and engineers with new questions and has resulted in development of new paradigms. For example, hydrologic science is now challenged to understand, quantify, and delineate the contribution of human land use change to flooding in comparison to those changes driven solely by anthropogenic changes in greenhouse gases. Hydrologic science has seen a transition in philosophy from strict river control to river control achieved through maintenance of river ecosystems and their natural geomorphology—a fundamental and controversial move away from flood conveyance to floodplain maintenance. A subdiscipline studying the exchange between surface and groundwater, termed "hyporheic exchange," has emerged. Conceptual advances in the hydrologic sciences extend beyond these Earth-centric environments as well. Evidence of water cycles on other planets, in particular Mars, has led to the entirely new science of exohydrology and the development of water-cycle models for planets. Hydrologic science has evolved into a science that both derives strength from other sciences and provides strength to other sciences and societal issues.

Although the advances mentioned above are not all-inclusive, these and other advances correspond to and describe an evolution of the context in which hydrology is done—an evolution that points the field in certain directions (for example, the development of models linking hillslopes to river connectivity across the landscape). Certain advancements in particular have allowed the community to understand, respond to, and address issues within this changing context. The committee anticipates that the field of hydrologic sciences will use these advances to surge ahead, in part because capabilities in such areas as imaging the Earth, measuring minute quantities of molecules in water and in organisms, performing calculations on amazingly fast computers, and employing techniques developed in microelectronics will enable the community to formulate and answer new questions and to approach recalcitrant old questions effectively. To underscore the advanced state of water science in 2012, the committee highlights four areas where progress has revolutionized hydrologic science—chemical analytical instrumentation, remote sensing and geophysics, embedded sensor systems, and computation. These also exemplify areas in which expectations of further progress indicate significant opportunities for future advances in hydrologic science.

Chemical Analytical Instrumentation

In Chapter 3 on critical and emerging scientific areas, the Blue Book acknowledged that tools and knowledge from the fields of environmental chemistry and aqueous geochemistry are key to understanding water movement, establishing erosional and climatic histories, and describing important biogeochemical processes such as solute transformation, ecological function, and contaminant fate. Since the publication of the Blue Book, there have been significant gains in making fast, accurate, and low-level chemical measurements of compounds in aquatic environments. These advances have greatly benefitted the hydrologic science community by helping to answer a wide range of hydrologic questions and providing the information for posing new ones.

Mass spectrometry (MS) is a technique used to determine the mass of particles or the chemical structure of molecules and was first applied in the mid-19th century. Since then, MS has been continually refined and advanced. Today it is a ubiquitous scientific tool that has evolved, for example, with the use of novel ionization techniques, through coupling with chromatography, and with the use of mass analyzers in a series. As a result, a variety of instrument configurations can produce more sensitive, cost-efficient, and specialized measurements. Geochemical applications of MS have dramatically changed since the Blue Book was published. Back then inductively coupled plasma mass spectrometry (ICP-MS), commercially introduced in the 1980s, was the state of the art for detecting most trace elements, especially transition and heavy metals, and stable isotope MS was (and still is today) used in a number of hydrologic applications (e.g., separation of baseflow and overland flow, dating of groundwater, etc.). Today, MS techniques in many labs utilize “nontraditional” stable isotope analysis, which included elements such as lithium and boron and now includes rock-forming and biologically important elements such as silicon and calcium, as well as many trace metals such as copper, molybdenum, and even mercury. These new techniques provide insights into geochemical and biogeochemical processes as well as describe water pathways.

In addition, development of the measurement technology to detect cosmogenically produced isotopes such as ^{10}Be and ^{26}Al in minerals has transformed the field of geomorphology by providing dates of topographic surfaces and rates and patterns of erosion processes. These measurements help set the stage for advancing the understanding of hydrologic processes (and the coupling to biotic and chemical processes) as well as providing ways to age-date hydrologic events such as glaciations and extreme floods. In another application, noble gas spectrometry is being used to estimate the age of groundwater, which is important for understanding impacts of groundwater pumping and rates of recharge.

The technology used to analyze more “traditional” stable isotopes (H, C, and O) has evolved to include portable, high-sensitivity cavity ring down spectroscopy approaches that are very low cost and involve far less maintenance and training compared to benchtop isotope-ratio mass spectrometers. These new endeavors will lead to more robust databases. For example, the Global Network of Isotopes in Rivers[2] globally monitors $\delta^{18}O$ and δD in river water, which allows for better assessment and evaluation of anthropogenic activities such as water storage and irrigation practices as well as climate change on river runoff.

Chromatography, a method used to separate and analyze complex chemical mixtures, is used extensively in scientific research. Like mass spectrometry, some instruments developed based on this fundamental technique have evolved over the past 20 years and have spread to a variety of scientific disciplines and subdisciplines, while others have remained mostly unchanged. Ion chromatography, used to separate ions and polar molecules based on their charge, allowing rapid and precise analysis of dissolved major ions such as fluoride, chloride, nitrate, nitrite, calcium, magnesium, and many others at low concentrations, has not changed significantly over the past 20 years. Yet newer chromatography techniques can now separate and detect of organic compounds (naturally and anthropogenically derived). These include the development of highly selective stationary phases and fundamental changes to the liquid chromatography (LC) hardware. For example the relatively recent development of ultra performance liquid chromatography (UPLC) pushes the bounds of traditional high-performance liquid chromatography (HPLC) by providing excellent analyte resolution coupled with rapid sample analysis.

Perhaps the most significant advance over the past two decades is the coupling of HPLC with MS (single and in tandem), which was accomplished through the development of electrospray ionization, a groundbreaking method used to ionize high-mass compounds with subsequent analysis by MS.[3] This method significantly expanded the suite of compounds identifiable by modern analytical techniques, and is critical in the identification of new contaminants in water around the globe. Used with HPLC or UPLC and tandem MS such as triple-quads or quadrupole-time-of-flight MS, this highly selective technique can elucidate complex chemical mixtures such as contaminants of emerging concern in complex environmental matrices.

The sophistication of many of these newer techniques and instruments has allowed for more detailed temporal or spatial sampling and analysis, enabling hydrologic scientists, engineers, aquatic geochemists, and envi-

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[2] See http://www-naweb.iaea.org/napc/ih/IHS_resources_gnir.html.

[3] John B. Fenn and Koichi Tanaka were awarded the Nobel Prize in Chemistry in 2002 for working on this ionization method.

ronmental chemists to unravel the impact of such processes as photosynthesis and photo-oxidation on transition-metal dynamics and speciation. An astounding number of new contaminants ("contaminants of emerging concern") have been detected in the aquatic environment. New and more sensitive geochemical and isotopic techniques have added to the ability to age-date and trace groundwater movement over various temporal and spatial scales. The presence of sophisticated analytical equipment extends into the field, as well. Hydrologic scientist are now deploying new *in situ* ("in position") analyzers or field-deployable boxes, especially for nutrient chemicals such as nitrate, that were originally developed by the oceanography community. These allow for higher-frequency temporal analysis and potentially almost real-time data return. Finally, fourier transform ion cyclotron resonance (FTICR) MS is one of the latest developments of MS to be applied to the hydrologic sciences. Developed in the 1970s, this high-resolution technique is one of the advanced methods—if not the most advanced method—of mass analysis with unprecedented resolution especially for larger and more complex organic molecules such as dissolved organic matter, proteins, and so on.

Remote Sensing and Geophysical Techniques

The inherent and pervasive irregularity of Earth's surface and subsurface properties presents an impasse in the ability to characterize and predict hydrologic processes. However, recent breakthroughs in satellite and remote imaging and sensing and ground-based geophysical techniques have provided unprecedented opportunities to break this impasse by collecting and analyzing a massive amount of field data. A few examples are provided, below, to highlight the currently available techniques that have contributed greatly to new ideas but have yet to be fully exploited in advancing hydrologic science.

Weather radar has facilitated spatially extensive estimates of rainfall that are unavailable using sparse rain gauge networks. For example, the completion of the Next Generation Radar (NEXRAD or WSR-88D[4]) surface-based radar network over the United States led to a synoptic view of evolving and migrating rainstorms that transformed both the researcher and the public view of this fundamental flux in the hydrologic system. The dynamic national composite precipitation maps, albeit with coarse measurement accuracy, inspired a new line of hydrometeorological research, including work done as part of the Advanced Hydrologic Prediction Service at the National Oceanic and Atmospheric Administration.[5] For example,

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[4] See http://www.roc.noaa.gov/WSR88D/.

[5] See http://water.weather.gov/ahps/.

there is now an almost real-time assessment capability for estimating the average recurrence interval of extreme rainfall events. National precipitation maps that track storms across the continent have brought about a new public appreciation of weather-related natural hazards. The upgrade of radars to allow for polarimetric measurements promises to significantly enhance the accuracy of continental precipitation mapping and to result in research quality high-resolution mapping of this important forcing of the hydrologic cycle.

The accuracy of current estimates of global precipitation monitoring, which are on a larger scale and based on new spaceborne sensors, is to within about 40 percent for precipitation rates in the range of 1 mm/h to 10 mm/h (Hou et al., 2008). Drizzle, heavy precipitation, and solid-phase precipitation are even more difficult to capture. The current data sets are formed by combining data from passive and active satellite sensors with data from precipitation gauges. The spatial resolution and data refresh rates are limited by today's technological capabilities. In the coming decades with the launch of the National Aeronautics and Space Administration's (NASA's) Global Precipitation Measurement (GPM) project,[6] which includes follow-on missions building on the success of the Tropical Rainfall Measuring Mission (TRMM) (Figure 1-1), a constellation of spaceborne sensors on board multiple satellite platforms will allow for mapping of global precipitation fields with unprecedented relative accuracy across a larger range of rain rates and with higher spatial and temporal resolutions.

Remotely sensed observations of many other land-surface conditions from current and forthcoming sensors on board spaceborne satellites and suborbital aircraft will provide ever greater streams of unprecedented high-resolution data on surface soil moisture, soil surface temperature, topography, vegetation structure and health, snow cover, and other variables. (For example, the satellite microgravity measurements described in Box 2-3 have proven extremely valuable for estimating groundwater depletion.) These data will allow hydrologists to examine patterns that could not otherwise be easily discerned and will potentially lead to new theories about hydrologic processes in relation to land-surface properties. The forthcoming Earth-observing NASA satellites now include instruments and missions that are principally justified by applications in the water-cycle sciences. For example, NASA's Soil Moisture Active Passive mission[7] that is in development and due to launch in 2014 is designed to produce high-resolution estimates of the near-surface (0-5 cm) soil moisture field and its frozen or thawed status. Similarly the GPM mission,[8] also in development and due

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[6] See http://pmm.nasa.gov/GPM.

[7] See http://smap.jpl.nasa.gov/.

[8] See http://pmm.nasa.gov/GPM.

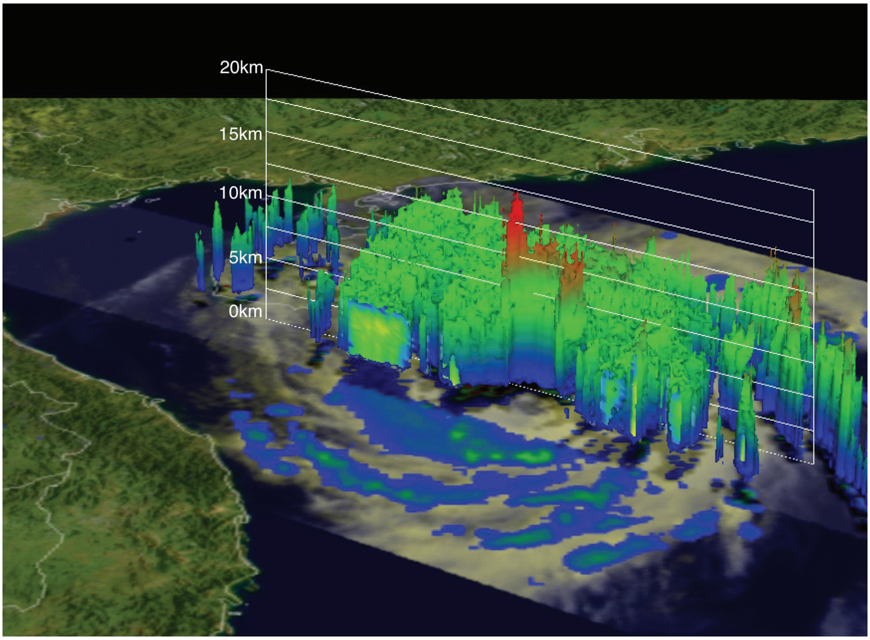

FIGURE 1-1 The microwave radar and radiometer instruments on board the Earth-orbiting Tropical Rainfall Measuring Mission (TRMM), launched in 1997, allow unprecedented insights into the three-dimensional structure of precipitating clouds. This image is of Typhoon Neoguri in the Southern Pacific, April 17, 2008. SOURCE: NASA's Earth Observatory, available online at http://trmm.gsfc.nasa.gov/trmm_rain/Events/neoguri_17apr08_0729_utc_15dbz.jpg and through the TRMM extreme event image archives, http://trmm.gsfc.nasa.gov.

to launch in 2014, will map global precipitation as part of a constellation of Earth-observing satellites. One of the main goals of the Surface Water and Ocean Topography mission,[9] which is under study for launch later in the decade, is to provide estimates of surface water extent, elevation, and slopes and therefore storage and storage change in lakes, reservoirs, wetlands, and rivers (especially flood plains) based on spaceborne measurements. Discharge will be modeled from those measurements.

In February 2000, during an 11-day mission using the Space Shuttle Endeavour, the Shuttle Radar Topography Mission produced a near global-scale, high-resolution (as fine as 30 m) digital topographic database of Earth. These digital elevation data quickly became the gateway data set for watershed studies and enabled studies of landscapes that had not been

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[9] See http://swot.jpl.nasa.gov/.

possible previously. Now the availability of lasers (using LiDAR, Light Detection and Ranging) to measure the elevation of the land surface provides the hydrologic community with yet another data source that potentially can change the discipline in fundamental ways. The discovery that water flows downhill is lost in antiquity (undoubtedly it occurred well before written history), but until fairly recently precise maps to indicate what direction was "downhill" at any point on Earth's surface were lacking. The ability to produce LiDAR maps at a vertical resolution of several centimeters enables new inferences to be drawn; for example, clear pictures of exactly where stream channels begin can be drawn (Figure 1-2). Other information relevant to hydrologic modeling that can be extracted from meter-scale,

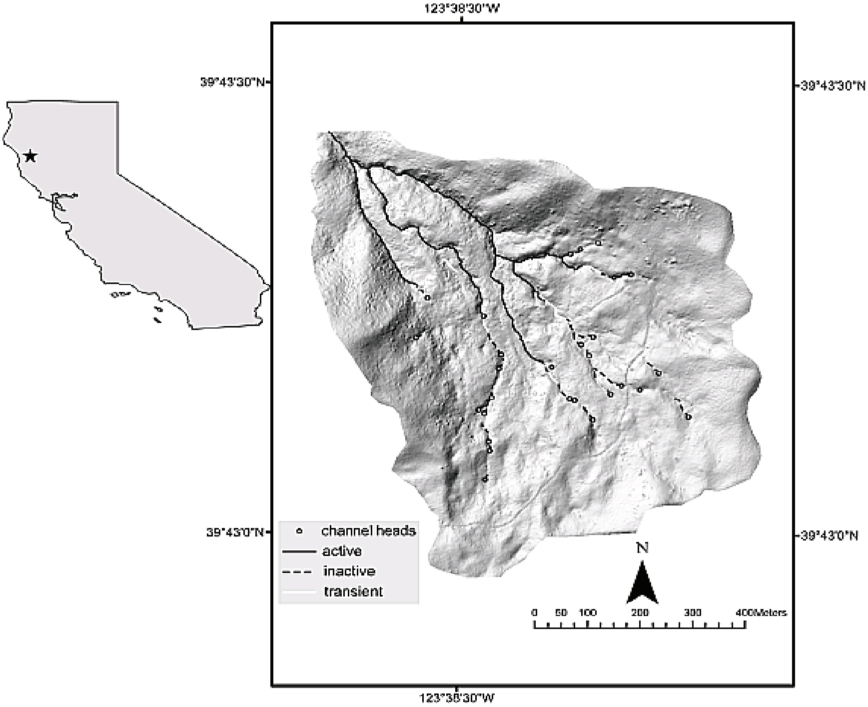

FIGURE 1-2 LiDAR has accuracy (error in height determination on the order of less than 20 cm), spatial resolution, and capability in sensing across vegetated and low-terrain landscapes, which allows for digital mapping of terrain that is excpetional when compared to those based on radar, stereographic optical, and other methods. In this example, a shaded relief image of ground surface that lies under a dense forest canopy in the Skunk Creek Watershed, Northern California, is shown. Data were collected from an aerial survey by the National Center for Airborne Laser Mapping, an NSF center. SOURCE: Reprinted, with permission, from Passalacqua et al. (2010). © 2010 by the American Geophysical Union.

high-resolution topography includes stream cross-section morphology, floodplains, landslide scars, roads and cuts contributing to sediment production during floods, and even vegetation height and biomass. Of course, with any new sensor come new challenges in data interpretation and accurate extraction of geomorphic features, requiring the development of filtering techniques that remove error while allowing accurate and automatic extraction of geomorphic features of interest (e.g., Passalacqua et al., 2010).

As a final example, geophysical characterization techniques provide opportunities to discover new processes that occur in soil waters and in groundwater. Recently it has been proposed that bacteria in the ground facilitate conduction of electricity (Revil et al., 2010). Thus, areas with high concentrations of bacteria (e.g., where contaminants may have stimulated bacterial growth) may be "visible" to geophysical techniques, which allow for creation of images using electrical signals (e.g., Figure 1-3). While these new observations are exciting, they generate research challenges in quantifying the uncertainty of these remotely sensed or multisensor merged

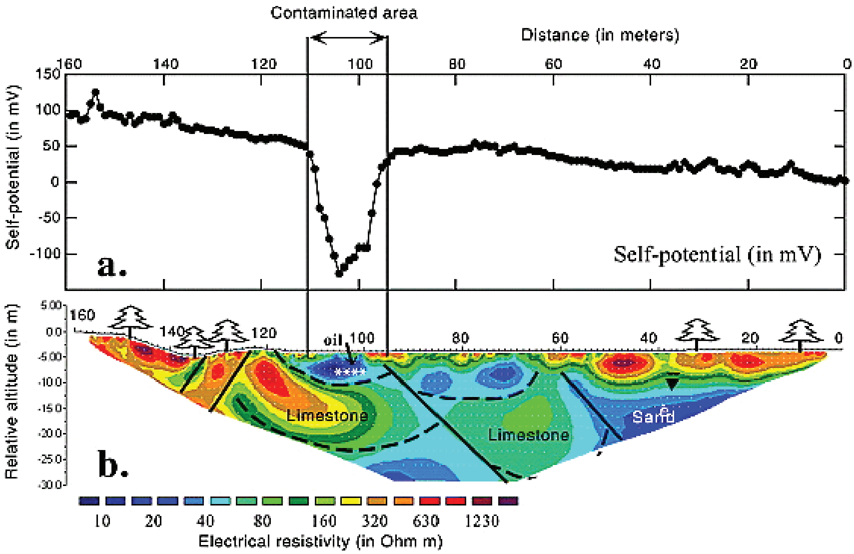

FIGURE 1-3 An oil spill in the south of France showing electrochemical signals in the ground where biodegradation is taking place. (a) Two electrodes measure the self-potential in mV and (b) the electrical resistivity of the site is shown in cross-section. This method offers a promising, nonintrusive method of detection for these spills. SOURCE: Reprinted, with permission, from Revil et al. (2010). © 2010 by the American Geophysical Union.

products and in understanding how this uncertainty propagates to hydrologic predictions.

Computation and Hydrologic Modeling

Computation continues to transform scientific research by enhancing what can be studied and generating new questions to ask and answer. Computers have been used in hydrologic research almost as long as they have been in existence. Numerical models for watersheds and groundwater reservoirs are widely available and used extensively by both practitioners and researchers.

Since the 1991 publication of the Blue Book, peak floating point operations per second of high-performance computers (a measure of a computer's performance) have increased around five orders of magnitude. Because of advances in computing power, hydrologists now can design numerical experiments that were impossible just a few decades ago (e.g., Kollet et al., 2011). Hydrologists now have the capability to study the spatially distributed feedback from the land surface and oceans to weather events and the climate system using realistic models of physical and biophysical processes at appropriate scales. Similarly, hydrologists can create models of groundwater flow that can resolve processes at quite fine scales and investigate hypotheses about geological controls on flows. Computations are carried out even at the atomic scale to understand how biogeochemical reactions take place on the mineral grains of a rock. Uncertainty analysis and optimization through Monte Carlo techniques will continue to transform application of hydrologic models. Beyond facilitating application of models, the added computational capability allows posing and addressing new science questions that were not possible previously.

As the field continues to expand the scope of its research, computers with far greater computational and storage capacity will be needed. Computation is the key to handling the massive amounts of data generated from, for example, Earth-observing satellites and real-time sensors. To keep pace with data generation, new tools to enhance community access and tools for data and model visualization will need to be developed. Advances will be required in data assimilation, which provides a synthesis of observations and increasingly sophisticated numerical models to provide detail on the movement, storage, and quality of water in and on Earth. Development of a community hydrologic model or modeling platform (Famiglietti et al., 2008) in a vein similar to the Community Climate Model developed by the National Center for Atmospheric Research has received recent attention and is likely to be pursued by the hydrologic sciences community in the future. Hydrologic science will benefit from the expected explosion of computing power in the future, just as the science has evolved in parallel with the computer revolution.

A Sensor Revolution

Advances in microelectronics have produced a host of useful measurement techniques, including tiny wireless sensors known as motes, complete with software and on-board low-power communication systems that can be deployed in watersheds, mounted on trees or structures, or embedded in the soil. These systems hold the promise of measuring across a relatively large scale (hundreds to 10,000 m) a wide variety of hydrologic and meteorological parameters at relatively low cost. As sensor cost continues to decline, due to demand within and outside the hydrologic sciences, arrays of wireless, autonomous sensing platforms have become an expected component of any watershed study. For example, similar arrays such as those used by Weather Underground have already captured the public's attention, providing web-based services to link the public with both scientific and personal meteorological stations across the world. The hydrologic sciences can benefit greatly by riding this "wave" of sensor and information technology. The potential for advancement in hydrologic science is described in a recent study:

> Sensors are being developed that are smaller, less expensive, and require less power, allowing for deployment in much larger numbers. Researchers are designing sensors to provide previously unavailable information, such as real-time measurements of nutrient concentrations in surface, soil, or groundwater. Sensors are being arrayed in networks that enable the sharing of information and hence produce synergistic gains in observational capacity; these sensor networks offer the promise of filling critical gaps between traditional point and remotely sensed measurements (NRC, 2008).

Advances in sensor technology make it possible to address questions on finer time scales than was possible in the past. Sensor arrays now routinely measure dissolved oxygen, nitrate, solar irradiance, and temperature in surface waters. For example, continuous in situ sensor data (Figure 1-4) were used to estimate gross primary production, ecosystem respiration, and nitrate uptake and from these estimates to partition nitrate uptake among organisms producing their own energy ("autotrophs") and denitrifiers. This kind of detailed information leads to new insights about how critical ecosystem processes such as gross primary production relate to nitrogen uptake at time scales ranging from minutes to seasons and yield insights into the dynamic connections between ecosystem energetics and nutrient kinetics.

Hydrologic science is also now utilizing a much wider range of sensors than ever before. For example, advances in distributed sensing along fiber

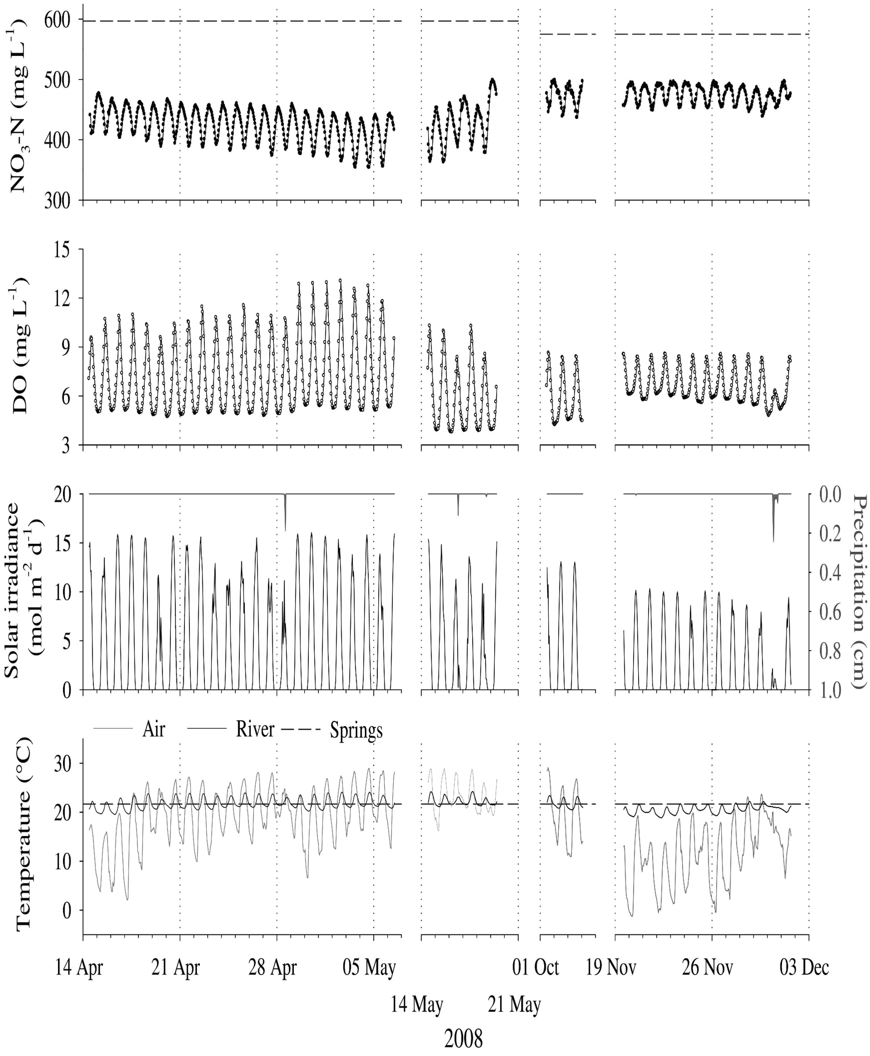

FIGURE 1-4 Continuous sensor data for temperature, solar irradiance, dissolved oxygen (DO), and nitrate (NO_3). These measurements were used to probe direct and indirect coupling of primary production and diel nitrate dynamics in a subtropical spring-fed river. SOURCE: Reprinted, with permission, from Heffernan and Cohen (2010). ©2010 by the American Society of Limnology and Oceanography.

optic cables, first developed for the petroleum and electric power industries, are becoming widely available and deployed for measuring temperature and strain almost continuously in time and space. The ability to measure temperature at very high spatial and temporal resolutions, using only the scattering properties of optical fibers, has brought tremendous insights into, for example, the fields of groundwater and surface interaction. Whereas in the past, hundreds of individual sensors would be needed to characterize the spatial patterns of groundwater inflows, along with daily stream energy budgets, these can now be easily measured using standard telecommunications optical fibers (Figure 1-5).

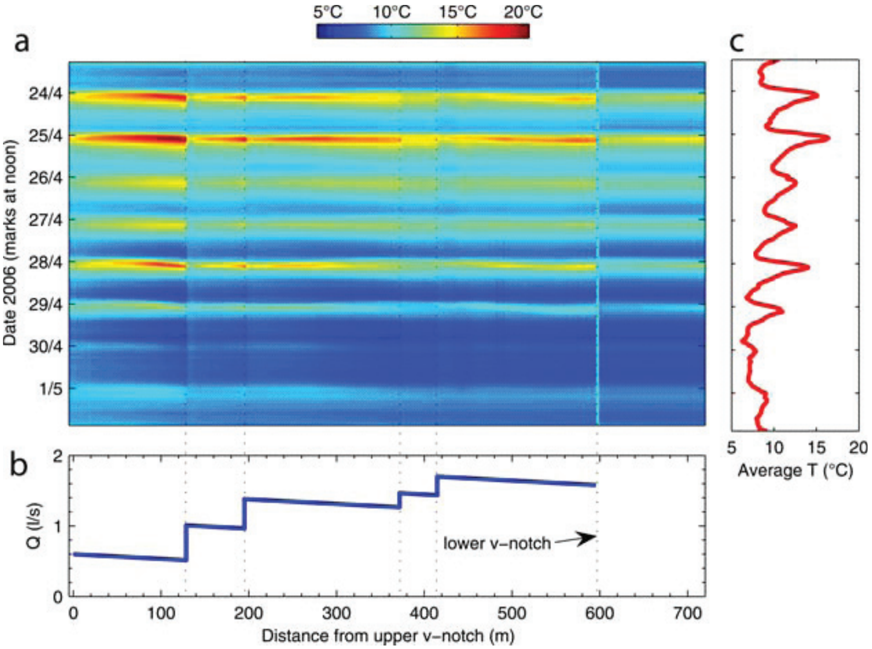

FIGURE 1-5 The time evolution of temperature along a 700-m reach of the Maisbich stream in Luxembourg using fiber-optic distributed temperature sensing. Distinct steps in stream temperature represent zones of upwelling groundwater, while the variation in both time and space in stream temperature are the result of variations in solar energy input and shading. This figure represents more than 8 million individual data points collected by a single instrument operating remotely and demonstrates the revolution in both spatial and temporal data that can now be collected. SOURCE: Reprinted, with permission, from Selker et al. (2006). © 2006 by the American Geophysical Union.

Twenty-five years ago, the subsurface was a data-poor environment constrained by a few point measurements. Today, operational measurements of soil moisture, soil temperature, and energy balances at very high spatial resolution are available. Advances in geophysical tools such as electric resistance tomography and ground-penetrating radar have led to much higher resolution maps of subsurface petrophysical properties. Significant challenges remain in translating the geophysical responses to traditional properties of interest such as hydraulic conductivity, but the field of hydrogeophysics has emerged to tackle these difficult questions.

Soil moisture, increasingly recognized as an important driver of climate along with coupled ocean and terrestrial processes such as monsoon cycles, has long been difficult to measure at the scales necessary for agriculture, meteorology, and hydrologic science. Most sensors to date (e.g., time-domain reflectometry) have been essentially point sensors providing a relatively accurate measurement, but one that was both difficult to scale up appropriately and expensive to obtain. Traditional microwave remote sensing can provide large spatial coverage (>1 km) but typically only interrogates the upper few millimeters to centimeters of the soil profile. In addition to the low-cost wireless sensing mentioned above, advances in both microwave sensing and other passive sensing systems now appear capable of bridging the gap between the point scale measurements of soil moisture and the watershed scale. Fiber-optic sensing, using buried fiber-optic cables and a variety of natural and induced heating, has been applied to estimate soil moisture distribution at the watershed scale. The recently developed Cosmic-ray Soil Moisture Observing System (COSMOS) utilizes the naturally produced cosmic ray neutron flux to infer hydrogen content (and therefore moisture content) at scales of 500 m to depths of 50 cm—scales very appropriate for catchment, agricultural, and advanced climate modeling (Desilets et al., 2010). Currently deployed at more than 30 sites in North America, these sensors represent a significant leap forward in the ability to measure hydrologic variables at the appropriate scales.

Higher temporal sampling and resolution has already been mentioned in light of biogeochemical cycling, however perhaps the greatest contribution of higher temporal sampling (coupled with more rapid data transmission) has been the near-real-time analysis of hydrologic fluxes across landscapes. Rather than a daily mean flow from a catchment, forecasters and the public now expect near-real-time and continuous streamflows and precipitation measures. Along with traditional sensors and the explosion in data transmission capacity, either by cell network, wireless, or Internet, new high temporal frequency techniques are constantly being developed. For example, the recognition that cellular phone tower communication is influenced by rainfall intensity along the path length of the transmission has led to the second-by-second reconstruction of rainfall rates in Europe (Messer et al., 2006).

The sensor revolution has enabled hydrologists to look at much higher spatial and temporal frequency processes that dominate hydrologic science. As in most scientific disciplines, higher resolution measurements lead to fundamental discoveries, e.g., Leeuwenhoek and his microscope.[10] Higher spatial resolution, through either less expensive point sensors or better resolution remote sensing, has allowed the discipline and its collaborative disciplines to radically alter its views of the rapidity of climate change (Taylor et al., 1993). Sensors have also furthered understanding of the architecture of subsurface heterogeneity, via hydrogeophysics, leading to fundamental theories of contaminant transport in the subsurface and have allowed using ever finer, analytical and X-ray tomography to understand the importance of the microscale distribution and the phase of geochemical constituents critical to human and ecosystem health.

Wireless self-organizing networks (e.g., Kido et al., 2008) are within the reach of any researcher, and new techniques are continuously being developed. The "sensor revolution" represents a fundamental advance in the field of hydrologic science. Testing, tuning, and maintaining fully operational sensors and sensor networks will, of course, continue to require expenditure of effort, particularly in those areas where sensors are not fully operational or remain costly. Fortunately, hydrologists will not work alone in this effort, because other research communities dependent upon environmental data, such as oceanography, environmental engineering, meteorology, and ecology, can provide synergy in sensor development, testing, and deployment. For hydrologic science, a more significant challenge will be to incorporate these sensor data into models that operate at coarser or similar high spatial resolutions.

THE INTERDISCIPLINARY INTERFACE

As a distinct geoscience, hydrologic science poses many important research questions that will be addressed by work within the discipline. However, the hydrologic cycle is a central element for many environmental disciplines that are neighbors to hydrologic science, and so it is not surprising that meeting many of the present and future challenges and opportunities will require collaboration among hydrologists, engineers, and scientists in other biogeoscience disciplines. Indeed, this collaboration has already

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[10] Antonie van Leeuwenhoek (1632-1723) is known for his contributions to improving the microscope, allowing unprecedented high-resolution observation of, for example, single-celled organisms. As a result, he is best known for his contribution toward establishing the field of microbiology.

begun. For example, the study of vegetation patterns has, until relatively recently, been segregated by discipline. Ecologists explored connections based on specific competition, biogeochemists sought explanations based on heterogeneous distributions of soil and rock chemical properties, and hydrologists and geomorphologists considered controls on fluxes of water and sediment. In reality, of course, complex interactions exist among a host of factors, and hydrologic science is important in almost all critical processes. As a result of this and other similar examples, new disciplines have emerged that define these new areas of research (e.g., hydroclimatology, hydrometeorology, geobiology, hydroecology, hydrogeomorphology, ecogeomorphology, and Earth-surface dynamics). Hydrologic science is central to all of these fields and, in being so, is becoming redefined by these fields.

> Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice.
>
> *Facilitating Interdisciplinary Research*, NRC, 2004

In addition to the scientific desire to delve into fascinating questions at disciplinary interfaces, emergence of high-profile, multifaceted problems such as water management and ecological restoration in California, restoration of the Everglades, Mississippi River nutrient loading and Gulf Hypoxia, sediment management in the Missouri River, and water management in the Colorado River basin highlights how collaboratively driven work is a critical component of research that focuses on real hydrologic phenomena. The committee mentions a few examples of areas where past collaborative research yielded major new insights and where future concerted effort is needed.

Paleohydrology is the science concerned with the study of hydrologic systems as they existed before direct observation and modern hydrologic records. This interdisciplinary field uses methods of analysis and information from hydrologic science, climate science, botany, and geology. Concern about the impacts of climate variability and change and the corresponding desire for forecasting changes have heightened interest and resulted in increased activity in this area, beginning in the early 1990s (NRC, 1991) extending to the present. An increasing number of high-resolution records have been developed over the past several decades, especially from tree rings. These records are important because they provide a more complete picture of past hydrology, documenting both spatial and temporal patterns of hydroclimatic variability over the past several millennia, and allowing recent hydrologic trends and events to be placed in a long-term context. Significant contributions include documentation of the spatial extent of droughts in many regions over North America over the past 2,000 years that indicate persistent droughts of much greater length and severity than any in the past century over broad areas of the western and southwestern parts of the United States (Figure 1-6). These droughts are also manifested in a multitude of watershed-scale reconstructions of streamflow, which are now being used by a number of water resource management agencies to plan for drought.

The linkages between ecology and hydrologic science at the land surface are complex and, like paleohydrology, scientific progress requires interdisciplinary collaboration. Water from the atmosphere as rain, snow, or dew obviously is essential for plants to thrive. But plants also affect the soil, which determines how much water is held for use by vegetation and how much is "lost" from the near-surface soils. Similarly, the atmosphere drives evaporation and transpiration (the movement of water from soils through plants to the atmosphere). Plant canopies create an environment

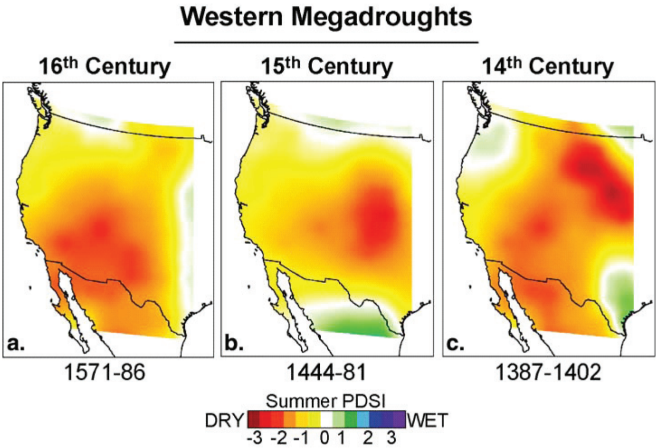

FIGURE 1-6 Droughts lasting for several decades have been identified by paleoclimatologists. Megadroughts during the 14th, 15th, and 16th centuries were determined using tree-ring reconstructed summer Palmer Drought Severity Indices (PDSI) averaged and mapped over the western United States. SOURCE: Reprinted, with permission, from Stahle et al. (2007). © 2007 by Springer Science and Business Media.

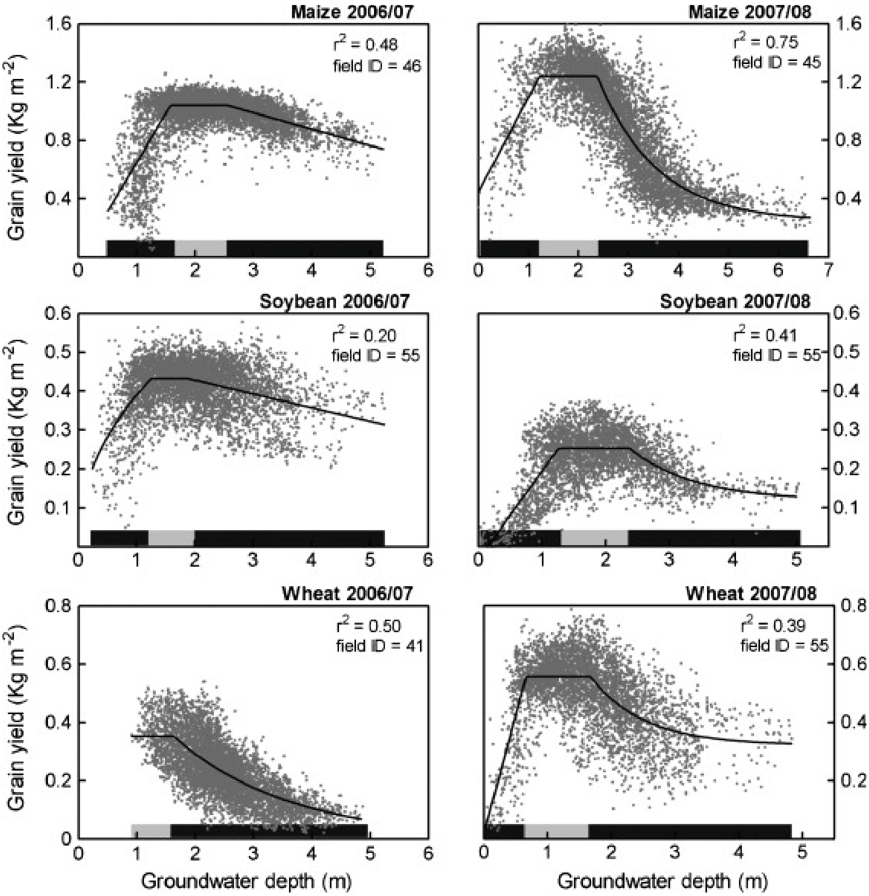

FIGURE 1-7 In agroecosystems crop yield is affected by groundwater depth, which in turn is affected by the use of water by plants. To identify groundwater depths that optimized crop yield, the authors combined data on corn, soybean, and wheat yields with topographic maps and groundwater-depth sampling. In this figure, piecewise regressions with two breakpoints were used. SOURCE: Reprinted, with permission, from Nosetto et al. (2009). © 2009 by Elsevier.

with different temperature and humidity relative to, say, a concrete parking lot and so affect the behavior of the atmosphere. Furthermore, soil properties affect how readily water and nutrients can be taken up from the soil by plant roots but again the growth of the roots themselves changes the soil structure, which is relevant to vadose zone hydrology, the subdiscipline concerned with water in soils.

Hydroecologic interrelationships are of considerable practical importance, for example in agriculture (Figure 1-7). Beginning in the late 1970s and 1980s, leading researchers from traditionally "agricultural" and "hydrogeology" backgrounds began to recognize that hydrologic processes from the soil surface to the water table were continuous and that collaboration among soil scientists and geologists was a fruitful way to make progress. Cross-fertilization between the agricultural and geologic communities led to advances in solute transport models, commercialization of field measurement systems, inclusion of vadose zone monitoring in waste disposal design and remediation, and recognition of the role of land use change and paleoclimates on fluxes to the water table.

Mechanisms exist to promote these and other interdisciplinary collaborations and are discussed in more detail in Chapter 5. For example, in recent years a group of scientists has worked collaboratively within the Critical Zone Network to investigate "processes within the Critical Zone, defined as the Earth's outer layer from vegetation canopy to the soil and groundwater that sustains human life."[11] Critical Zone Observatories (CZOs) study the operation and evolution of the Critical Zone. (For more information, see Box 3-1.) These collaborations are in the spirit of discovering fundamental relationships among physical and biological processes where expertise from the fields of geosciences, hydrologic science, microbiology, ecology, and soil science participates. Problems being addressed range from acid mine drainage to release of arsenic to groundwater.

HYDROLOGIC SCIENCE: LOOKING AHEAD

Important challenges lie ahead in understanding the complexity of the Earth system, and water will never cease to play an important role in that system (NSF, 2009). Almost 20 years after its publication, the Blue Book remains fresh and compelling, and its statements take on even greater urgency in view of a stressed planet:

> [Water] … is a hazard, a resource to be managed, and an enabler and sustainer of civilization. It is important to and affected by physical, chemical and biologic processes within all compartments of the earth system: the atmosphere, glaciers and ice sheets, solid earth, rivers, lakes and oceans. Water vapor is the working fluid of the atmospheric heat engine; water, as the primary greenhouse gas, is instrumental in setting planetary temperature; water, through fluvial erosion and sedimentation, together with tectonics, shapes the land surface; water, is the universal solvent and the agent of element cycling. Finally, water is necessary for life.… (NRC, 1991)

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[11] See http://www.czen.org/.

The hydrologic community should be ready to face the complex water-related challenges of today and tomorrow by continuing disciplinary and interdisciplinary research toward a predictive understanding of the atmosphere-hydrosphere-biosphere-lithosphere system from the microscopic to the global scale, by continuing the transformation of hydrologic education to ensure the workforce needed for the years ahead, and by translating new scientific understanding to decision-making tools for solutions that achieve sustainable outcomes.

The NSF recognized the significance of emerging water issues and the need to strengthen and adjust its hydrologic science research efforts to address these issues. NSF acknowledges that understanding the complexity of the Earth system, which is driven by water, is critically important. It also recognizes the importance of interdisciplinary efforts among its various programs, divisions, directorates, and other agencies. The present study was undertaken by the NRC's Water Science and Technology Board at the request of NSF Earth Sciences officials.[12] The committee's charge is to review the current status of hydrology and its subfields and the coupling with related geosciences and biosciences, and to identify promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment (Box 1-2).

With respect to the restrictions of the study to not make budgetary recommendations or to critique existing NSF programs, embedded within the statement of task was certain language that the committee interpreted as a request from the NSF for specific advice pertaining to the foundation. This includes reference in the task to current research modalities,[13] educational opportunities, and strengthening observational systems, data management, modeling capacity, and collaborations including interfaces with mission agencies. These capabilities are integral to the NSF Hydrologic Science program and other NSF programs within the foundation; they represent the mechanism(s) used to promote the foundation's mission.[14] In addition,

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[12] Original language from the study proposal that was included in the grant from the National Science Foundation to the National Research Council authorizing and scoping the study is as follows: "The primary focus of this study will be the NSF program in hydrologic science but given the importance of water issues to the nation, the report should also serve the academic/educational community, other agencies with programs in hydrology and water resources, Congressional staff, the Office of Science and Technology Policy, professional societies, and other entities with missions related to Earth sciences and water resources."

[13] The committee interprets the term "modalities" in the statement of task as referring to capabilities within the NSF and other federal agencies used to advance hydrologic research including contracts and research grants, instrumentation and facilities, and so forth.

[14] To "promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…"; see http://www.nsf.gov/about/.

BOX 1-2
Statement of Task

This study will identify the challenges and opportunities in the hydrologic sciences, including (1) a review of the current status of the hydrology and its subfields and of their coupling with related geosciences and biosciences, and (2) the identification of promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment. The goal is to target new research directions that utilize the capabilities of new technologies and not to critique existing programs at NSF or elsewhere. The resulting report will not make budgetary recommendations.

Specifically, the study will:

- Identify important and emerging issues in hydrology and related sciences,
- Assess how current research modalities impact the ability of hydrologic sciences to address important and emerging issues,
- Identify needs and research and education opportunities for making significant advances in hydrologic sciences, and
- Assess current capabilities in and identify opportunities to strengthen observational systems, data management, modeling capacity, and collaborations needed to support continued advancement of hydrologic sciences, and also their relationships to and value for mission-related agencies and, reciprocally, how observational systems of mission-related agencies relate to and contribute to hydrologic sciences.

these capabilities are integral to other agencies and organizations that support research in the hydrologic sciences.

The Committee on Challenges and Opportunities in the Hydrologic Sciences met six times, heard presentations from scientists and engineers who work in several areas of hydrologic science and related disciplines, and solicited input from the community at an open town hall meeting at the 2009 Fall Meeting of the American Geophysical Union. Despite fundamental progress in the field, the challenges and opportunities that lie ahead have intensified rather than diminished in view of the increasing pressure on Earth's water resources. Many open questions demand renewed and strategic research in the field. Water shapes landscapes and life, which, in turn, affect water flows and stored volumes of water. How do hydrologic systems, landscapes, and their biological communities co-evolve? Scientists are learning more and more from records encoded in rocks, trees, and ice. How does knowledge about the hydrologic past prepare us for society's water future? Does the planet face shrinking ice and growing deserts? How are bioclimatic zones evolving? Humans continue to intervene in the hydrologic cycle of Earth via diversions, dams, and pumps. What are the consequences of this planetary "replumbing?" Can sufficient clean water be supplied where and when humans and natural ecosystems need it? Through a host of natural and human-induced changes, ecosystems have been altered extensively. How can scientists tell if freshwater ecosystems are broken and, when they are found to be broken, how can they be fixed? How much water does an ecosystem need? Arguably the most important advance in public health came toward the end of the 19th century when water contamination was recognized as the cause of widespread disease outbreaks such as cholera, and sanitation was introduced. Yet today society still grapples with issues related to water quality. Can water quality be assessed and managed to protect human and ecosystem health? How can new detection, treatment, and modeling tools be used to protect the public against contaminants of emerging concern?

The questions posed above are examples of intriguing puzzles that engage scientists and engineers in hydrologic science and related disciplines. A discussion of such questions could be organized along many different pathways. This committee chose to write three separate chapters, which stand on their own but are intimately linked, that cover fundamental questions in hydrologic science and related biogeosciences. All three chapters present examples of "curiosity-driven" and "problem-driven" research; both are important. The sum of these chapters is not an exhaustive list spanning the entire range of hydrologic and related research. Rather, it is intended to enumerate some of the most challenging concepts and to identify some of the research areas most important to promoting progress in the field.

The research opportunities in each chapter are arranged into several sections paired with a succinct **boldface statement** intended to extend the meaning of the section title as well as to interest and inspire the reader. Some of these areas will obviously overlap, a reflection of the intertwined, high-level challenges facing the community. Each section drills down into more specific, *italicized questions* and ends with specific exemplary questions for readers seeking more detail. The tiered structure of the central chapters is intended to cater to an audience ranging from the aspiring hydrologist or engineer seeking an introduction to hydrologic research to an established scientist seeking detailed information. The chapters contain numerous boxes and figures to draw attention to interesting contributions and examples, and to support concepts articulated in the surrounding text. The committee cited publications only when critical: to properly attribute a figure or image, quotation, point of fact, or explicit concept, thus avoiding a literature review. The reference section at the end of each chapter contains references not only called out in the text but also from key citations ("Suggested Reading") that provide additional source material as an educational tool and a resource for aspiring scientists. The Suggested Reading lists are composed of review papers, synthesis documents, or landmark papers to provide the reader with material containing both depth and breadth on a given issue.

The report is designed to be of use to members of the hydrologic community, mainly the research community, which includes not only academics but scientists and engineers from the private sector, federal agencies (most notably the NSF Hydrologic Science program and other Earth Science programs within NSF, when appropriate), decision makers interested in water research and policy, and those with Earth sciences and water resource-related missions interested in where hydrologic science fits into the surface-earth sciences. The report is also written for graduate and undergraduate students seeking inspiration, general knowledge, or guidance when selecting a focus within the field. Although the primary audience is the hydrologic community, the challenges and opportunities are intentionally broad, illustrating the necessity of interdisciplinary work needed to face the complex water related challenges of today and tomorrow.[15]

The signature of a scientific challenge is that it is compelling—both in the domain of intellectual curiosity as well as in the domain of consequences for human and ecosystem welfare. The following chapters, titled "The Water Cycle: An Agent of Change," "Water and Life," and "Clean Water for People and Ecosystems," outline major areas of opportunity and challenge for hydrologic science. The content of each is intended to be a vision statement, identifying areas that deserve emphasis because they present challenges and opportunities which are both intellectually compelling and socially relevant to human and ecosystem welfare. The fifth and final chapter also discusses the challenges and opportunities, but in the context of accomplishing these goals for the hydrologic community and, more specifically, NSF. This chapter points out that "translational hydrology"—highly collaborative work that includes social scientists and a wide variety of stakeholders—will be required to establish a healthy, resilient, and sustainable planet.

Opportunities in the Hydrologic Sciences cemented the foundation of the field. Hydrologic science in the 21st century is a broad field that encompasses all of traditional hydrologic science as defined in *Opportunities in the Hydrologic Sciences* and extends into areas that are traditionally of interest to other fields and related subdisciplines. This report builds on that foundation by stressing not only further building of hydrologic science, but also the interdisciplinary potential of a science with an established foundation.

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[15] The committee was asked to report on challenges and opportunities in the hydrologic sciences. The charge was not to discuss the distinction between "scientists" and "engineers."

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2

The Water Cycle: An Agent of Change

Water has helped shape our planet to produce the world in which we now live. Knowing how water has acted throughout Earth's history and how water cycles function on other planets will broaden our understanding of how Earth's water cycle functions. This knowledge will allow us to better predict how human and natural factors will combine to produce the world we leave to our children and our children's children.

INTRODUCTION

Water plays multiple roles in the evolving physical system of the planet. It shapes the landscape as rivers and glaciers flow over the surface, waves break on shorelines, and freeze-thaw cycles crumble rocks. Water influences the movement of energy through the climate system as a greenhouse gas absorbing radiation and reemitting it to the surface; a reflector of sunlight when condensed into clouds, snow, and ice; and a transporter of heat when evaporating, circulating, and condensing; it influences the distribution of Earth's gravity field. The distribution of water affects the location and character of life, the movement of Earth's crust, and even the rotation rate of the planet. The flow, phase changes, accumulation, and dispersal of water around the world—the water cycle—vary substantially with time and location. Thus, water does not respond passively to physical processes governing Earth: it is a dynamic agent whose influence is central to processes that produced today's world and that will affect its evolution into the future.

Human intervention in the water cycle alters water's dynamic role on the planet. Humans have become major agents alongside nature in the functioning of the water cycle, through water management and changes in the land, atmosphere, and ocean that alter natural water processes. Humans also are altering Earth's climate, which produces further changes in the water cycle. Hydrologic and related sciences require credible accounting of water to assess how the water cycle acts and will change. Such accounting is needed for timely and accurate prediction of natural hazards, including "abrupt" or irreversible changes, and relies on basic understanding of interacting processes, that is, understanding how the world works.

Scientific and technological advances now offer exceptional opportunity to develop a comprehensive understanding of water's pervasive activity throughout the Earth system over periods ranging from early epochs to the present and future. Although many disciplines can contribute to this opportunity, hydrologic science plays a central role, as highlighted in this report. Over the past several decades, the knowledge of Earth as a system has grown considerably through new observational techniques, analysis methods, and computing tools, all of which have helped hydrology mature as a discipline (see Chapter 1). This maturation has given hydrologic science a leading role in advancing understanding of the water cycle and the processes that affect and are affected by it over a range of scales and environments. As part of this leadership, hydrologists and engineers have forged links with closely related disciplines, especially the atmospheric, soil, plant, and cryospheric sciences (which deal with snow, ice, and frozen ground) to develop a more comprehensive and coherent view of water as a central component in Earth's climate system.

Admittedly, how water acts varies significantly across time scales ranging from seconds to decades and longer, and spatial scales from millimeters to planetary, thus presenting a very complex dynamic picture and a monumental task in monitoring all its storage and transport aspects. However, advances in observing systems and computing allow use of computational techniques such as data assimilation that could support development of this comprehensive view by merging observation sources into a unified, global portrayal of water with unprecedented temporal and spatial detail. New observing systems such as space-based platforms coupled with global networks of existing observing tools could produce global, real-time views of where water is and where it is going, in all its phases (Gao et al., 2010; Wong et al., 2011). The sensor revolution is in its nascent stages, but for the first time the promise of closing the global and regional water budgets with direct measurement of flux and storage components may be just within reach. Opportunities also exist to extend this portrayal of water into the future. Scientific advances have contributed to progress in understanding the interactions between water and other Earth system components, leading to modeling of the water cycle as part of a comprehensive Earth system simulation system. Yet an opportunity exists for models providing plausible scenarios of the impact of climate change and land use change on the regional water cycle.

Stepping away from the contemporary and future perspective, examination of water flow and storage during periods ranging over the past decades, centuries, millennia, and into deep geologic time offers opportunity to understand how Earth's water cycle evolved to its present state. Equally important, understanding the range, frequency, and rate of change of past behavior provides a baseline of natural variability as well as a means to gauge the impact of humans on the water cycle, which can be helpful now and in forecasting the future. New methods of data acquisition and refinement of existing techniques yield an expanding set of paleoclimate data that shed new light on past hydrology. Further advances could provide longer views with yet finer temporal and spatial detail. Just as modeling has shed new light on contemporary and potential future water cycle behavior, modeling past climates guided by advances in paleoclimate reconstruction can further test the limits of knowledge, as expressed by models, while also revealing physical insight that complements proxy records.

Stepping away from considering the Earth alone, the understanding of Earth's water history gains from comparison with alternative planetary evolution pathways. Advances in planetary science have broadened understanding of where and how planets and moons form, both in the solar system and beyond. Awareness of the emergence and evolution within the solar system of "water cycles" based on water or other condensing constituents (e.g., methane) provides unparalleled opportunity to reveal cosmological principles that guided the formation of Earth and its water cycle. The discovery of terrestrial extrasolar planets potentially broadens that perspective even more.

RESEARCH OPPORTUNITIES

In this section, the committee discusses several research opportunities for the hydrologic sciences and presents underlying research questions. The research opportunities are ordered as in the Introduction above, focusing on challenges involving human influences and on contemporary and near-future hydrology (i.e., water-process measurements and modeling), then considering challenges and opportunities involving hydroclimatic variability, from abrupt changes to long-term variability, including the paleoclimate perspective, and finally considering the opportunities posed by exohydrology.

2.1. Human Influences on Water Availability and Distribution

The hydrologic cycle is being perturbed and "replumbed" through human activities.

The hydrologic cycle has been described and depicted in a variety of different ways, most frequently as a natural system, even though it has long been altered by human activity. Alterations of the hydrologic cycle for agriculture, transportation, and domestic and industrial needs have amplified dramatically over the past century, along with building of infrastructure in the form of dams and canals (Figure 2-1). In particular, population growth and development in arid and semi-arid regions where surface water is scarce have led to large reservoirs, diversion projects, and intensive groundwater pumping. These practices have had major impacts on surface and groundwater supplies, which have in turn impacted the downstream systems reliant on these supplies.

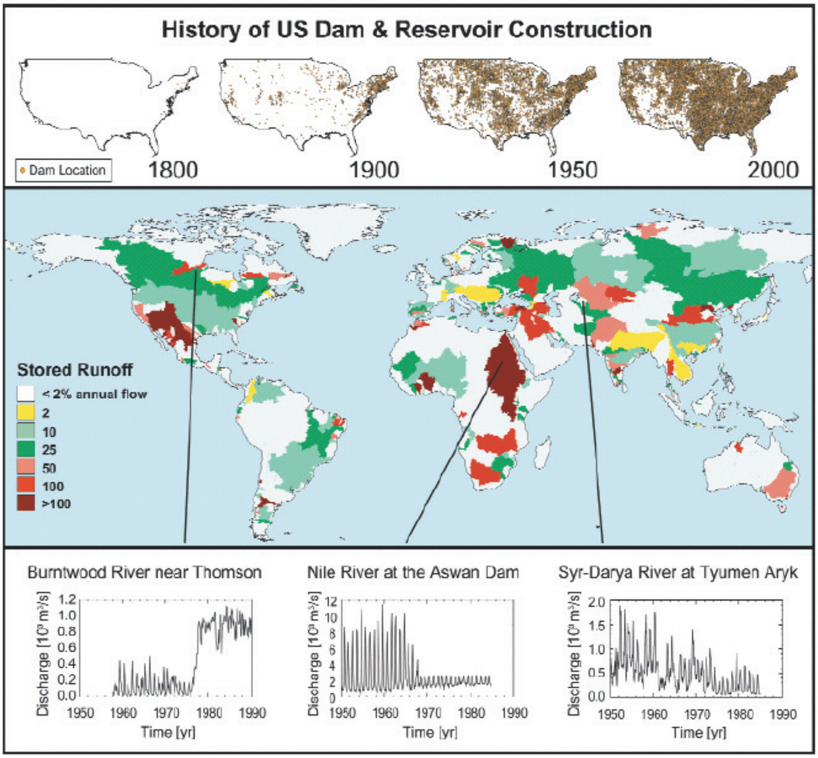

FIGURE 2-1 Alteration of the water cycle in the form of dams and canals is embedded deeply within the modern global water cycle. In the United States, the geographical extent of dams and reservoirs has increased dramatically over the past 200 years (top). This trend extends to developed parts of the world, with river regulation expanding rapidly in the 20th century (middle). As a result, human engineering and water use distort hydrographs (bottom). The left-hand graph is a purposeful interbasin transfer for hydroelectric production, the middle is the Aswan High Dam impact, and the right-hand is flow depletion due to cotton production in the Aral Sea contributing basin. SOURCE: Reprinted, with permission, from Vörösmarty et al. (2004). © 2004 by the American Geophysical Union.

The hydrologic cycle is altered by not only direct physical alteration, but also anthropogenic climate change; the most obvious symptom is the global redistribution of precipitation and the resulting change in surface water flow (Figure 2-2). In turn, changing the terrestrial branch of the water cycle impacts climate by altering the surface energy balance, changing evapotranspiration and surface reflectance characteristics. The hydrology of the land surface is affected directly by warming temperatures due to changes in snow and ice cover and shifts in vegetation patterns. The causes of hydrologic replumbing (land use change, hydrologic storage, climate change, etc.) are not independent and can yield compounding and cascading effects. For example, dam construction in arid regions impacts downstream hydrology and ecosystems, and additional stresses due to climate change challenge dam operations that strive to meet competing needs and further impact conditions downstream.

In addition to scientific issues, sociopolitical issues often take center stage. As an example, picture a semi-arid area of urban growth with limited water supply. Historically, water in many of these regions has largely supported agriculture, but in recent decades, the water needs of urban centers have become more dominant. When this shift in water demand involves transfer of water rights, tension between urban and rural areas can impact

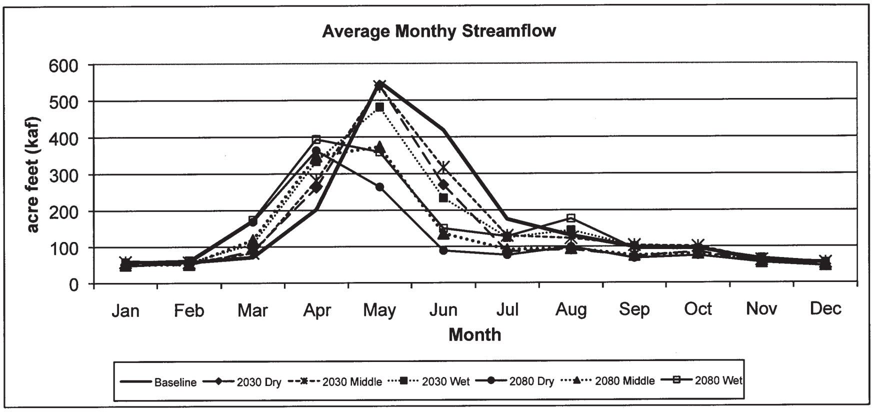

FIGURE 2-2 Average aggregate (based on seven upper Rio Grande basin tributaries) streamflow by month for six climate change scenarios. Three climate change models represent the range of possible climate outcomes for New Mexico (wet, dry, and middle) in 2030 and 2080. These projections illustrate that peak flow and total streamflow decline for all climate scenarios in this basin. In 2080, there is a pronounced shift in the peak runoff month, by about 30 days. SOURCE: Reprinted, with permission, from Hurd and Coonrod (2008). © 2008 New Mexico State University.

the amount of water available for agricultural communities. Infrastructure put into place to supply water for growing urban centers can impact surrounding ecosystems, creating an additional layer of tension. Finally, the impact of climate change introduces additional stresses on the hydrologic resources of the area.

In recognition of the human influence on the Earth system and in the context of Earth history, many scientists now call present times the "Anthropocene." The traditional concept of the hydrologic cycle should perhaps by revised to consider humans as a significant and recognizable component. Research to further understand the human component of the water cycle, i.e., human-induced replumbing from both climate change and land use change, is recommended. This understanding is critical to providing and maintaining water supplies for humans and ecosystems.

How will water distribution and availability change because of hydrologic replumbing?

Water-related infrastructure has allowed many parts of the world to flourish, but at a cost to the natural environment and with growing and unintended impacts on society and ecosystems (Box 2-1). The relationship between human consumptive use and available water is not fully understood, yet this information is essential to understand how distribution and availability will change in the near and distant future. The hydrologic community can shed light on this relationship by probing how replumbing perturbs hydrologic fluxes. What are the impacts of groundwater overdraft on the surrounding hydrologic regime? Finding answers to questions such as this one will further the larger, societal goals of encouraging the best conservation behaviors and pursuing water-efficient products, both of which should be accomplished with the best possible scientific information to assist fair, legal, and scientifically sound decision making.

Conservation measures have been increasingly applied as water availability has become more limited, but even measures designed to conserve water can have downstream impacts. In some cases, agricultural return flows have become an important source of water, as exemplified well in the Cienega de Santa Clara, an open-water wetland in northern Mexico, which is supported by the return flows from the lower Colorado River basin. The Cienega is threatened by the Yuma Desalting Plant through which return flows would be diverted to the plant for desalination. Thus, actions that change the natural hydrologic system often have complex and interacting impacts and can create competition for highly limited available water. These include actions with direct impacts on the water cycle, such as changes in water use, as well as those with indirect impacts, such as forest clearing. What are the downstream consequences of replumbing in terms of the amount and rate of flow and seasonality? What are the repercussions on both society and natural environments?

One recent focus has been on what is commonly called the "water-energy nexus" in which the human need for water is linked to energy just as tightly is the human need for energy linked to water. The procurement and delivery of water often requires energy for pumping, transport, desalination, and treatment. Likewise, almost all sources of energy, except perhaps wind, require water for some aspect of production (e.g., extraction, cooling, or conveyance), and many energy sources use considerable amounts of water. Of the freshwater used by the United States, 39 percent is used for electricity from fossil fuels and nuclear energy, and of that, as of 1995, 71 percent of that amount was used solely for the generation of fossil-fuel electricity (Solley et al., 1998). Oil shale and gas production, along with mining, have used a smaller portion of the freshwater in the United States, at 5 percent of the total withdrawn from surface and groundwater supplies. The increased use in the United States of biofuels, often touted as "green" energy sources (Box 2-2), provides another example. These uses highlight how increasing demands for energy correspond to increasing demands for water. The age of "separate but equal" resource planning for water and energy resources has passed—water is withdrawn and consumed during the life cycle of almost every energy source. What are the impacts of energy-related replumbing on water distribution and availability?

How will climate change influence the delivery of moisture (i.e., the severity, duration, and extent of droughts and floods)?

Climate change is expected to impact key hydrologic fluxes, most notably precipitation, which translates to impacts on the severity, duration, and extent of droughts and floods. A clear picture of the manifestation of climate change in floods and droughts has yet to emerge. Of course, increased vulnerability to hydroclimate extremes may be exacerbated by social and political factors, and having better scientific information may be of only limited value. For example, encroachment of construction in floodplains is a primary cause of increased damages (e.g., Pinter, 2005). Research opportunities exist, challenging the hydrologic community to provide better scientific information upon which social-political action will be required.

Flooding in the United States is linked to diverse regional climatologies of heavy rainfall. Extratropical cyclones, "atmospheric rivers" (Leung and Qian, 2009), rain on snow events, and convective storms are some of the most important flood agents in the western United States. Tropical cyclones, warm-season thunderstorm systems, and cold-season extratropical cyclones play important roles in the flood hydrology of the eastern United States (Smith et al., 2011), with their relative importance strongly dependent on

BOX 2-1

Is the North China Plain Running Out of Groundwater?

Groundwater overexploitation or persistent aquifer storage depletion is a worldwide phenomenon (Konikow and Kendy, 2005). Restricting their analysis to subhumid to arid areas, Wada et al. (2010) estimated that the total global groundwater depletion more than doubled from 1960 to 2000. The confluence of a multitude of factors, including rapid economic development, high population density, and climate change, makes the North China Plain (NCP) a compelling case study of a groundwater resource in peril (Zheng et al., 2010). The NCP refers to a relatively flat, low-lying alluvial plain in eastern China with a total area of 140,000 km^2. It is home to the capital city Beijing and several other large cities including Tianjin and Shijiazhuang. Approximately 130 million people now live within the administrative borders of the NCP. With a population density of about 900 people per km^2, the NCP is among the most densely populated regions in the world. The NCP is also critically important to Chinese economy, contributing about 12 percent of China's gross domestic product and producing more than 10 percent of China's total grain output.

The amount of exploitable water resource per capita in the NCP is in the "absolute water scarcity" category according to the "water stress index" (Falkenmark et al., 1989). Meanwhile, annual precipitation has steadily decreased by approximately 100 mm since the 1950s. In recent years, with dwindling surface water supplies, groundwater has become a primary source of water supply for the NCP. According to Zheng et al. (2010), more than 70 percent of the NCP's total water supply comes from groundwater to support the region's agricultural irrigation, industrial expansion, and population growth. The question is, how much longer can this be sustained?

The NCP sits on an expansive Quaternary aquifer system. The thickness of the NCP aquifer is tens of meters on the western piedmont areas but increases to hundreds of meters toward the eastern coastal areas. The NCP aquifer is commonly divided into two hydraulically connected units, referred to as the "shallow" aquifer and "deep" aquifer. During the "predevelopment" period until the 1950s, the water table of the shallow aquifer was usually no more than 3 m below the land surface in most of the NCP. Since the 1960s to 1970s, however, ever-increasing groundwater pumping has caused massive and continuing depletion in the NCP aquifer. According to the latest data from the China Geological Survey, the maximum depths to water in the shallow and deep aquifers exceeded 65 m and 110 m, respectively, in the shallow and deep parts of the NCP aquifer. Since the 1970s, groundwater levels in many parts of the NCP aquifer have declined at a rate of more than 1 m annually (Figure 2-3).

More than mere depletion of an invaluable natural resource, the overexploitation of the groundwater resource in the NCP has other severe environmental and ecological consequences, including dried-up rivers, land subsidence, seawater intrusion, and water quality deterioration (Figure 2-4). For the NCP's main river, the Haihe River, the annual runoff to the Bohai Sea has decreased by threefold since the 1950s. Moreover, much of the surface water has disappeared. More than 4,000 km of various river channels in the NCP have dried up and the total size of wetlands has decreased to 20 percent of their level in the 1970s. Land subsidence has also exerted a heavy toll on the region's economic development, especially near the major industrial and coastal city of Tianjin where the maximum cumulative amount of land subsidence exceeded 3 m. For the NCP as a whole, a total area of 60,000 km^2 has experienced a cumulative subsidence of 0.2 m or more.

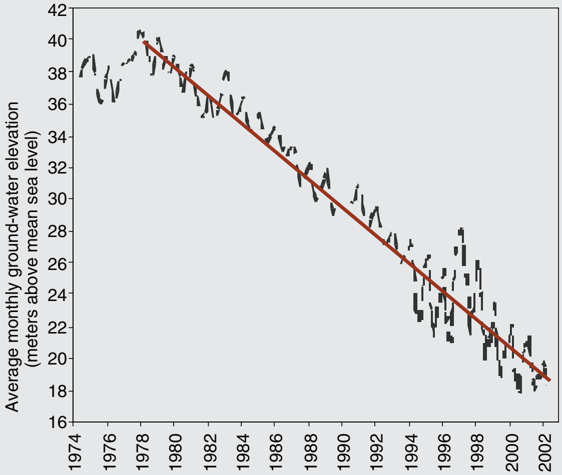

FIGURE 2-3 The long-term decrease in groundwater elevation at an observation well near Shijiazhuang City, Hebei Province, northern China. SOURCE: China Geological Survey (2009).

FIGURE 2-4 Eco-environmental consequences of groundwater depletion in China: a bridge over a dried-up river (left); former riverbed used for farming (right). SOURCE: Photos courtesy of Chunmiao Zheng, University of Alabama.

BOX 2-2
Water and Energy: Biofuels in the United States

Motivated by an increasing national interest in energy independence as well as concerns about the impact of greenhouse gas producing fuels, the United States has taken legislative steps to encourage the development of technologies that reduce dependence on these types of fuels. These steps include a new bioenergy program, which set the goal of developing technologies to generate biofuels that are price competitive with gasoline or diesel fuels. Although ethanol production could help achieve the national long-term goal of weaning the nation off greenhouse gas producing fuels, it comes at a cost to water resources, with regard to both water availability and water quality. Water is consumed not only in the production of crops to generate biofuels but also in the refineries that produce ethanol. Much of the water needed to cultivate biofuels relies on irrigation that taps limited surface and groundwater supplies, notably the Ogallala aquifer, and that compete with water supplies already used to support food production (NRC, 2007). An increase in the use of fertilizers to support additional crop yields for biofuel results in nutrient and pesticide pollution with corresponding impacts on water quality, including hypoxia, that endanger aquatic ecosystems (NRC, 2007).

The average water consumed in ethanol production, based on data from 19 states that produced ethanol in 2007, is 142 million liters of water for each million liters of ethanol, but this number is highly variable from region to region, ranging from 5 to 2,139 million liters (Chiu et al., 2009). The toll on regions where irrigation is necessary is evident. In 2003, a U.S. General Accountability Office survey indicated that many of the states that currently produce ethanol will experience water shortages over the next decade. Some of the states most likely to undergo shortages include those that consume the largest amount of water in the cultivation of corn and processing of ethanol, i.e., Colorado, Kansas, Oklahoma, and Wyoming (Chiu et al., 2009).

As of 2008, corn was used to produce more than 95 percent of the U.S. supply of bioethanol (EPA, 2008). Corn genetics research, water-conserving irrigation practices, and water pricing could help alleviate water stress in the production of corn-based ethanol (Chiu et al., 2009; NRC, 2007). Also, alternative sources of biofuels, such as sugar cane, oil seeds, the nonstarch parts of the corn plant, grasses, trees, and municipal wastes, may be less water intensive than corn and are being explored to determine their potential in terms of energy conversion efficiency and water quality impacts (NRC, 2007). Regardless of the source, the likely expansion of future production of biofuels has the potential to increase the demand for water in many parts of the United States (NRC, 2007).

drainage basin scale (Miller, 1990). Mesoscale convective systems have been the agents of extreme flooding in the central United States, notably during the Great Flood of 1993 and the Iowa flood of June 2008 (Coleman and Budikova, 2010). The Iowa floods were made worse by a heavy snow year resulting in greater than normal antecedent soil moisture for that time of year which prevented the mesoscale precipitation from infiltrating. How heavy rainfall translates into flood frequency and magnitude requires substantial hydrologic insight. However, all of these processes leading to flooding may change as climate change alters the water cycle, so insight built from years of experience in watersheds is undermined by climate change and associated changes in heavy rainfall. Furthermore, changes to the landscape by humans will add to the challenge. Research is needed to assess how changing rainfall patterns coupled with changing land use can affect floods and their impact in the future.

Another consequence of climate change is a potential expansion and further drying of a semicontinuous band of aridity in subtropical latitudes. Temperatures in all regions are projected to increase, but an intensification of the equatorial to subtropical circulation, called the Hadley cell circulation, is expected to result in a poleward expansion of the global latitudinal bands of aridity (Held and Soden, 2006; Lu et al., 2007) and with further reductions in precipitation. The impacts of this increased aridity will be felt in regions such as the U.S. Southwest and the Mediterranean region of Europe, with related impacts on water supplies for human and natural systems. On a more regional scale, research suggests that the winter-spring storm track over North America may be retracting poleward earlier in the season, leading to reduced spring precipitation in the western United States, a shift consistent with climate change projections under warmer conditions. Also, the moisture variability and occurrence of drought in regional climates in many parts of the world are strongly influenced by El Niño/Southern Oscillation (ENSO), a coupled ocean-atmosphere pattern of circulation in the tropical Pacific Ocean associated with climate in many parts of the world. In fact, the relationship between precipitation and ENSO is chaotic in some regions. In the California Sierra Nevada, for example, El Niño years are either wet or dry but generally not near the median. But research results do not agree on the impact of climate change on ENSO, and therefore this issue remains to be resolved. Planning for future water resources in these regions should evolve in the face of an anticipated reduction in precipitation. Research is needed, for example, to determine optimal measures for water management as precipitation declines.

Additional factors can amplify the impacts of climate change. For example, depending on location and climate regime, glacier meltwater provides essential water resources throughout the year, and in some locations it acts as a supplementary water source in the summer. Glacier loss due to climate warming and other factors could impact water resources in these areas, especially semi-arid and arid regions. Although many glaciers have exhibited recession over recent decades, with the highest retreat exhibited in glaciers at lower elevations, the rates of retreat can vary widely as regional factors (precipitation, aerosol concentration, etc.) affect glaciers in addition to warming. Regardless, the possibility exists that regions dependent on glacial melt will face increased periods of water shortage, with increases in both frequency and severity of drought. As the glaciers recede, basic research probing the major impacts on water supplies and flow regimes should be pursued. What modeling efforts are needed to better understand the connection between changes in the upstream glacier-water catchments and available water resources downstream? What new technologies, either airborne or spaceborne, can be used to further understand and characterize the human impact on the world's glaciers?

> A "grand challenge" thus faces the climate and hydrologic sciences communities—to understand the nature of ongoing changes in climate and hydrology and the apparent anomalies that exist in reconciling their extreme manifestations.
>
> *Global Change and Extreme Hydrology: Testing Conventional Wisdom,* NRC, 2011

More broadly, human-caused modifications of the water cycle through climate change can promote feedbacks that push the climate into new regimes. It has been speculated, for example, that climate change has removed the climate system out of the repeated cycle of glacial-interglacial episodes. Understanding the scope and nature of hydroclimate changes requires reliable, long observational records, accurate results from global and regional circulation models, and a full understanding of the causes of climate mode shifts even under natural climate variability.

The committee challenges the hydrologic community to reduce the gaps in knowledge of how the hydrologic cycle will respond to climate change. More specifically, how will changes in precipitation patterns affect the flow between and storage of water in the world's hydrologic reservoirs such as glaciers, lakes, rivers, and aquifers? How will changes in these reservoirs amplify or buffer regional hydrologic variability and change? Where, when, and how will couplings between reservoirs affect water resources?

What are the challenges in developing and using regional climate change projections for assessing future hydrologic change and impacts?

Long-term water resource management involves anticipating changes in demand and supply. Predicting basin-scale changes in water availability in response to climate change and hydrologic replumbing remains an obstacle to effective water resources planning and management. To extrapolate from what is known about global climate change to how flooding will increase in a given river basin years in the future so decision makers can, for example, identify a safe location for a nuclear power plant, involves numerous components (models, observations, etc.) appropriately linked with uncertainty minimized. Similar challenges exist to predict how climate change will affect regional water availability. For example, in a Mediterranean climate such as California, earlier snowmelt and precipitation that falls as rain instead of snow because of warming can result in less water in storage during the peak water demand season, which in turn stresses groundwater supplies. Runoff projections require coupling of climate models at both the global and regional scales, which feed into hydrologic models and often then into planning and operations models. Furthermore, it is now well known that important feedbacks to climate can occur from terrestrial hydrologic processes such as soil moisture and groundwater fluctuations, necessitating coupling of hydrologic and climate models for improved climate projections.

Global climate models (GCMs) have improved significantly over the past decades, with increases in spatial resolution and the incorporation of expanded hydrologic and biogeochemical processes into many models. Certain aspects related to the water cycle could still be modeled better, including cloud and cryosphere feedbacks and extreme precipitation events. At the regional scale, methods are being refined that use statistical and dynamical downscaling of GCMs to the scales relevant to climate change adaptation planning. At the watershed scale, hydrologic simulation models are used to project future conditions by incorporating downscaled GCM output. Challenges remain concerning the scalability of model behavior and generalization of results to watersheds with different characteristics. These linked challenges can be illustrated by a suite of studies that have targeted the Colorado River basin to reconcile projected changes in runoff during the next 50 years. Several different research groups using different sets of models, modeling approaches, and output recently narrowed the spread of projections from a 5 to 45 percent reduction to a 5 to 20 percent reduction in annual flow, a range that is still rather broad for useful planning purposes but nonetheless capable of exposing vulnerabilities in current management plans (Christensen and Lettenmaier, 2006).

Thus, uncertainties result from a chain of cascading factors, from the GCMs used, to how output is downscaled, and to the type of hydrologic model used to produce runoff projections. For operations and planning, the hydrologic output is then routed into operations models that include effects of increasing demand, changes in land use, legalities, and socioeconomic factors, all of which present additional uncertainties. The scientific challenge is significant and complicated by the fact that hydrologic science is not the only discipline needed to address the issue. Yet in essence, hydrologists and engineers have entered a new era in which quantitative analysis of the entire terrestrial hydrologic cycle is becoming possible. To promote this possibility, research to further integrate hydrologic models as well as to couple them with climate models is suggested.

To generate more useful hydroclimate projections from models, the following key research questions should be tackled: What is the capacity for models to project the frequency and magnitude of seasonal and longer periods with high precipitation or drought similar to that documented in paleoclimate records? Can model projections incorporate the impacts of human activities on regional climate and thus be more useful for management and planning? Embedded in many of these challenges is the need for hydrologists and other scientists to engage and interact with water resource professionals to solve problems related to the availability of adequate water quantities and quality for humans and natural systems. Although this is further discussed in Chapter 5, a few relevant questions are posed here: What are the most productive approaches for bringing together scientists and decision makers to address sciences questions that are relevant to planning and policy? How can management strategies be refined in the face of known uncertainties in regional climate variability and change? What educational programs are needed to train the next generation of hydrologic and climate scientists who are capable of both integrating the appropriate sets of hydrologic and climate measurements and fully coupling hydrologic and climate models to estimate future water resources availability?

2.2. Critical and Unknown Hydrologic Fluxes

Evaporation, transpiration, and groundwater fluxes interconnect the water, energy, and biogeochemical cycles and are conditioned by human impacts on the water cycle.

The water balance, incorporating land evaporation and transpiration (evapotranspiration) and groundwater fluxes (recharge and discharge), to the first order, determines the distribution of vegetation. In other words, these fluxes connect the water cycle and the biosphere, in addition to connecting the slow (subsurface), surface, and fast (atmosphere) components of the terrestrial water cycle. The time scales of the underground, slow components of the water cycle span decades. In contrast, the memory of the atmospheric branch is only days to weeks. By linking these disparate components, the fluxes serve as important regulators of the water cycle's dynamics. Land evaporation and recharge are directly relevant to the determination of the limits of sustainable irrigated agriculture and aquifer use. Recharge, as the rate of aquifer replenishment, is a key determinant of the sustainable rate of aquifer pumping. Maintaining land evaporation at a rate that does not stress vegetation is the primary factor that determines sustainable crop production and healthy ecosystems.

Understanding the processes that link the components of the water cycle is no less important than understanding the human impact on the water cycle itself. This understanding requires direct information on the patterns and dynamics of evapotranspiration and groundwater fluxes. Currently scientists do not even know the climatology, i.e., the average spatial and temporal characteristics, of fluxes over large land regions (Jiménez et al., 2011; Mueller et al., 2011). Yet the necessary tools for making progress in this area are close at hand. Spaceborne sensors can be deployed that map the state of surface soil moisture, surface temperature, water storage in Earth's crust (Box 2-3), and other conditions related to the hydrology of the land surface that impose important constraints on the estimation of evaporation and recharge. Two examples of important research questions are presented below.

What types and mixtures of remote sensing measurements, ground-based measurements, and modeling can be designed to yield estimates of evaporation and recharge fields at the landscape, regional, and continental scales?

The flux of water from the land to the atmosphere is complicated by the fact that much of it occurs through plants or as transpiration. The control of plant physiology over transpiration is difficult to deduce because of the complexity of biology and diversity of life. Furthermore, the turbulence generated in the boundary layer at the interface of the land and atmosphere is a key determinant of evaporation and transpiration. The difficulty in characterizing how turbulence is generated at solid-fluid interfaces—especially when the solid is rough, porous, flexible, and irregular—poses a challenge for mapping evaporation. Will improved understanding of plant physiology yield better understanding of how plants influence the water cycle? Can modeling strategies that advance understanding of flow through porous media improve estimates of evapotranspiration?

Evaporation and recharge are important to Earth's metabolism through more than just the water cycle. Evaporation is also part of the energy and carbon cycles and recharge is part of several biogeochemical cycles. Therefore, observations of many variables, such as land surface temperature, atmospheric carbon dioxide content, isotopes of carbon, and water and other compounds, can provide important information about evaporation and transpiration in addition to measurements routinely used to make estimates simply using the primary water-balance components, precipitation and stream flow. Models that simulate as well as integrate observations

BOX 2-3
Gravity Recovery and Climate Experiment Measurement of Changes in Earth's Water Mass

The Gravity Recovery and Climate Experiment (GRACE) is a twin satellite mission launched in 2002 by the National Aeronautics and Space Administration (NASA) and the Deutsche Forschungsanstalt für Luft und Raumfahrt.[a] The purpose of the mission is to map variations of Earth's gravitational field at approximately monthly intervals using global positioning system (GPS) and a microwave ranging system to make accurate measurements of the distance between the two satellites. Because the largest contribution to the change in Earth's gravitational field is from changes in distribution of water and snow, hydrologists use GRACE data to estimate changes in water storage at regional and global scales. Availability of GRACE data has contributed significantly to calculation of large-scale water balances that now can include a subsurface component.

A striking example of an application is the calculation of the amount of water flowing through the Amazon River basin (Figure 2-5). Other applications include detection of anthropogenic changes; recently GRACE data were used to confirm groundwater depletion over northern India resulting from unsustainable consumption of groundwater for irrigation (Rodell et al., 2009). In addition, several studies point to the feasibility of using GRACE data for subcontinental and regional-scale assessments. Examples include the High Plains aquifer (Strassberg et al., 2007), the state of Illinois (Swenson et al., 2006; Yeh et al., 2006), and the Mississippi River basin and its subbasins (Rodell et al., 2007).

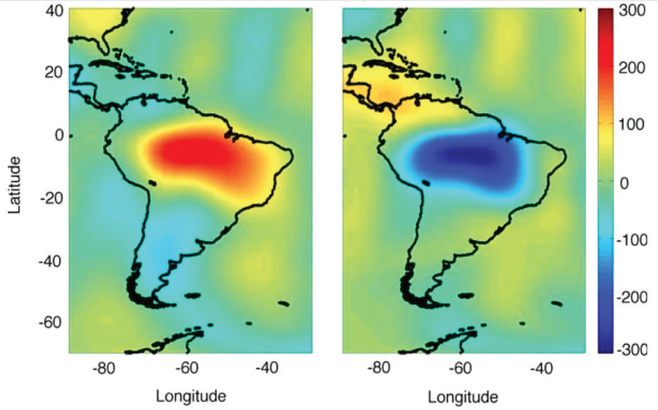

FIGURE 2-5 Selected illustrations of monthly water changes over the Amazon and neighboring regions. The distinct rainy and dry seasons of the Amazon show up clearly in these monthly maps (left, April 2005; right, October 2005). SOURCE: Reprinted, with permission, from Crowley et al. (2008). © 2008 Springer Science + Business Media.

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[a] See http://www.csr.utexas.edu/grace/.

will need to evolve to incorporate new observations. Data assimilation, the systematic blending of observations and models, can progress to finer time and space scales as computing power increases and assimilation methods and models become more sophisticated. Data assimilation offers the potential for developing physically coherent, observationally constrained data sets that depict Earth's combined water, energy, and biogeochemical cycles. What are the key uncertainties that impede improved assimilation outcomes for hydrologic variables? How can assimilation make optimal use of coupled biogeochemical cycles to limit uncertainty in hydrologic fields?

The number of spaceborne and airborne platforms are growing, and the data streams from the instruments located on these platforms can contribute to estimates of the key land-surface fluxes—where water is going in all of its phases (Box 2-3). The mapping capability of these platforms is particularly suitable for spatially extensive estimation. Furthermore, advances in sensor technologies now allow measurements with spectral resolution that can sense complex chemicals; the combined estimation of water and biogeochemical fluxes may improve accuracy of measurement of both. In situ sensor developments—including those relying on remote sensing such as acoustic, seismic, and electrical geophysical exploration—allow new and detailed types of measurements that are relevant to characterizing evaporation and recharge. The hydrologic community should not only adopt emerging sensors but also guide the development of their next generation. How should the community implement new testbeds for technology development that focus on developing and cross-testing emerging sensor technologies? What community field experiments are needed to determine key unknowns? What principles from theory should guide campaigns of observations?

How are groundwater fluxes coupled to surface landscapes and waterscapes?

Recharge fluxes, from Earth's surface to groundwater, are notably difficult to characterize. Recharge occurs deep in the soil column beyond immediate reach. It can be focused in some narrow conductive corridors that are difficult to find and map. Recharge also can be diffuse but occurs at rates so small that it requires deployment of sensitive sensors at depth, a difficult technological task. Finally, focused recharge can be intermittent in time and short lived.

Discharge fluxes, from groundwater to Earth's surface, occur to streams and rivers, lakes, and the ocean, to the land surface itself in springs and seeps, or directly to plant roots that emit water into the atmosphere via transpiration. Groundwater discharge also can originate from recharge at distant locations in other watersheds connected by long, groundwater flow paths. Groundwater discharge is measured more often than recharge because it tends to be geographically more focused or localized. Nevertheless, because of its distributed nature, extensive data, or even appropriate measurements, are commonly not available. Therefore, knowledge of spatial and temporal patterns of discharge is therefore fragmentary at best. Groundwater development has resulted in another major groundwater discharge mechanism, the pumping from wells. Knowledge of well pumping rates is also fragmentary because they are seldom measured (NRC, 2004).

Groundwater fluxes at interfaces depend on land cover, climate, soil and rock properties, and topography. Hydrologists traditionally have worked to understand how these factors "control" fluxes. In a larger sense, however, groundwater fluxes impact the development of the soil, land surface, vegetation and soil biota, topography, and climate. Thus, developing a fuller understanding of groundwater fluxes at interfaces, at least over time scales beyond the hydrologic year, present very interesting scientific challenges. For example, groundwater discharge occurs in wetlands with extensive peat. How do fluxes sustain the low-oxygen environments necessary for peat formation? If groundwater fluxes in these systems decline, how does the drying of peat in turn affect water (and nutrient) fluxes? There are poorly understood connections between climate and groundwater fluxes. Changes in both temperature and precipitation affect infiltration and thus patterns of diffuse groundwater recharge. How does climate change over the span of years or decades alter the water balance at Earth's surface and lead to changes in vegetation patterns and consequently a variety of surface processes? Conversely, near-term changes in recharge can have large impacts on groundwater discharge in the distant future. Can the relationships between groundwater and climate be discerned through the careful study of paleohydrology?

Groundwater fluxes at interfaces can often be inferred using remote sensing, typically during times when the temperature of discharging groundwater is much different than the temperature of the surface water body. These data provide information about broad patterns of discharge. To fully quantify discharge, the remote sensing patterns should be linked with field measurements made at discrete locations. Integration of information and data generated at different scales is essential to learn about details of process and pattern. How do the measurements at small scales translate to observed variability as one moves up in scale? What are the essential elements of a research program for improving estimates and measurements of groundwater recharge and discharge across scales? To quote from a National Research Council (NRC) report on recharge and discharge, badly needed is:

> the development of sensors that measure recharge and discharge at "point" scales, research to increase our understanding of the scaling of these mea-

surements and underlying processes, the development of procedures for integrating measurements and observations across scales, and generation of mathematical tools to assimilate and synthesize observations at all scales into groundwater process models (NRC, 2004).

2.3. Understanding Variability at Multiple, Coupled Scales

Processes that define water fluxes occur at the scale of turbulent gusts of wind to large weather systems and from the scale of the first drops of water that initiate streams to the complex system of rivers that define drainage basins.

The past few decades have witnessed not only major advances in understanding and modeling the space-time variability of hydrologic processes including precipitation, soil moisture, and streamflow, but also, more importantly, development of conceptual frameworks for describing this variability across a wide range of scales, from physical, phenomenological, and statistical perspectives. For example, empirical evidence from several watersheds of different physiographic and hydroclimatic conditions has for decades demonstrated how "self-similarity" or "scale invariance" in mean annual streamflows manifests itself in simple power-law relationships, generally referred to as scaling laws. Although the scaling of mean annual flows (with exponent of approximately 0.5 to 0.6; e.g., see Figure 2-6, bottom panel) has been attributed to the topologic structure of river networks, the physical origin of scaling laws for specific storm hydrograph peaks (e.g., the emergence of scaling with exponent of 0.79 for the storm of June 2008 in Figure 2-6, middle panel) remains an unsolved problem. Because observations cannot be made all the time and everywhere in a watershed and because physically based distributed hydrologic models require extensive data for calibration and verification, such simple scaling predictive theories are not only of theoretical interest but also of immense practical importance.

The committee presents two important problems that further challenge predictive understanding of hydrologic variability across a range of scales, from small subbasins of a few square kilometers to large basins of the order of tens of thousands of kilometers. The first relates to the dynamic connectivity of landscapes, from hillslopes to the subsurface and to fluvial river networks, and how it may manifest in scaling theories of hydrologic response. The second relates to human amplification of natural variability and change over a range of spatial and temporal scales.

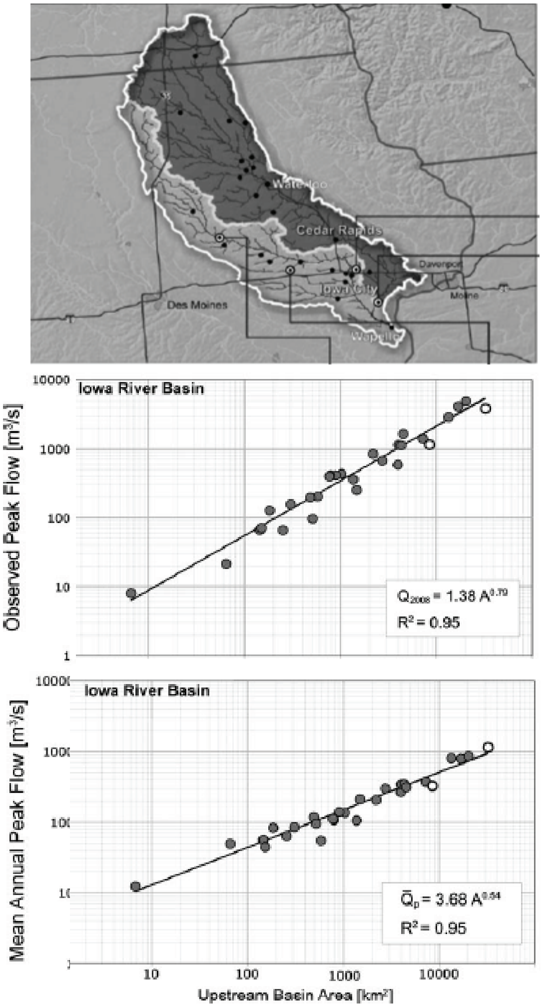

FIGURE 2-6 Emergence of scaling in both mean annual floods (bottom) and storm-specific floods (middle) in the Iowa River Basin. The 32,400 km^2 Iowa River basin has 29 daily recording U.S. Geological Survey stream gauges (top) forming the basis for the scaling plots shown (middle, bottom). The mean annual peak flow scaling reflects the topologic structure of the river network, but understanding the scaling of the observed peak flow for the storm of 2008 remains a challenge. Empty circles are locations where stream gage records are affected by upstream regulation or replumbing. Note that the middle panel corresponds to the catastrophic flood of June 17, 2008, which resulted in total damage of 10 billion USD, caused 85 counties to be declared disaster areas by the President, and displaced 40,000 people. SOURCE: Modified, with permission, from Gupta et al. (2010). © 2010 by the American Geophysical Union.

How do flowpaths along hillslopes and the subsurface, which connect to the stream network intermittently in time and with spatially variable extent, influence runoff dynamics over a range of space-time scales?

Understanding how processes at the small scale (hillslope) interact with those at the larger scale (networks) to describe the entire hydrologic response of river basins and the possible emergent scaling laws for specific rainfall-runoff events remains elusive. Analysis of the connectivity of the river network to the three-dimensional landscape within which it is embedded (e.g., intermittent exchanges between riparian and stream zones (Figure 2-7), dynamic surface-to-subsurface interactions, and space-time variable contribution of hillslopes to streams) has exposed the limitations of current conceptual theories that attempt to generalize hydrologic response as a function of scale.

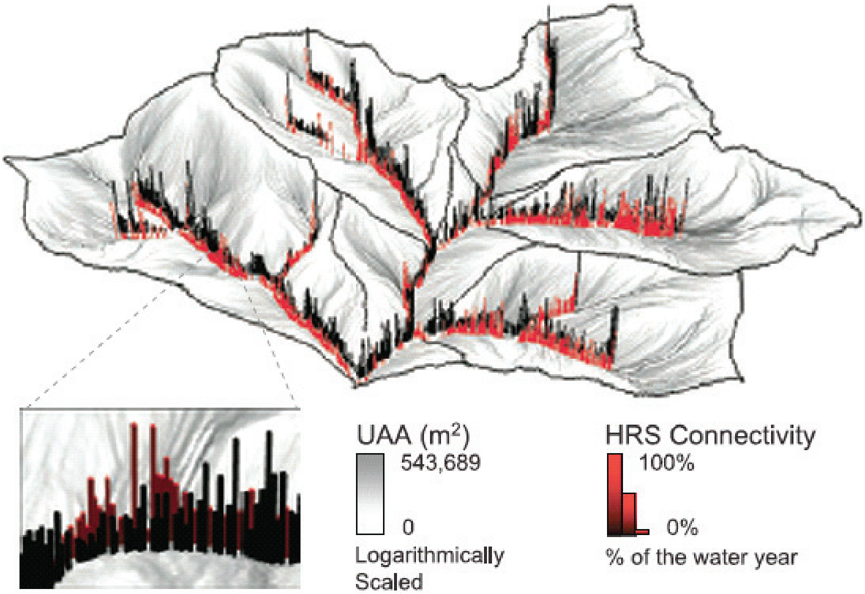

FIGURE 2-7 An illustration of hydrologic connectivity in terms of the upstream accumulation area (UAA; shaded) for a location and the percentage of the water year for which there exists hillslope-riparian stream (HRS) water table connectivity along the left (red bars) and right (black bars) sides of the Tenderfoot Creek network, Montana. The predicted hydrologic connectivity ranges from 0 to 100 percent of the year (represented by bar heights) and is a first-order control on the catchment scale runoff dynamics. SOURCE: Reprinted, with permission, from Jencso et al. (2009). © 2009 by the American Geophysical Union.

The nature of dynamic pathways that connect the unchannelized part of the basin (98 percent of the landscape) to the river network (hardly 5 percent of the total landscape area)[1] is complex and carries the signature of the space-time variable storm structure as well as the soil and vegetation dynamics of the basin. Yet, general organizing principles still exist, and observations suggest that scaling laws in streamflows might still apply at the storm scale, reflecting a generalized scale invariance of the co-evolving system. Process-based theories of hydrologic response on "extended" networks (encompassing hillslope, subsurface, and fluvial flow paths) should be developed, aided by new high-resolution topography data via light detection and ranging (LiDAR) and verified by detailed hydrologic observations over a range of space-time scales and climates. These new approaches can address a variety of research questions. For example, how can dynamic pathway connectivity and space-time variable precipitation be incorporated into a generalized scaling framework of hydrologic response? Can the static template of the river network be transformed into a dynamic template (expanding or contracting or disconnected network of paths) over which flows and other fluxes are organized over a range of space and time scales? Finally, can network theories be adopted for dynamic (space-time) scaling of fluxes and how could the scaling parameters emerge from physical properties of the system?

Given that interactions at overlapping scales change hydrologic patterns in subtle ways, how can hydrologists disentangle human-induced landscape changes from the observed hydrologic response?

Human impacts on the landscape, such as clear-cutting, increased fire frequency, land use changes, and replumbing of the landscape via surface tilling and subsurface tiling[2] for increased crop production, are changing delivery of water to streams. A changing climate further modifies the landscape. The result is a streamflow signal that differs from previous decades (Figure 2-8). A challenge of theoretical and practical interest is to develop a predictive understanding of the two-way interactions between human impacts on the landscape and the climate system and how these impacts may manifest in the hydrologic response. For example, what changes in streamflow patterns are attributable to changing precipitation patterns, changing crop practices, or both, and how can they be disentangled and predicted in the future? What magnitudes and frequencies of human-induced landscape

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[1] These values are estimates based on committee experience with drainage density and channel width as inferred from light detection and ranging (LiDAR).

[2] Subsurface tiling is a piping system underneath agricultural lands for draining excess water.

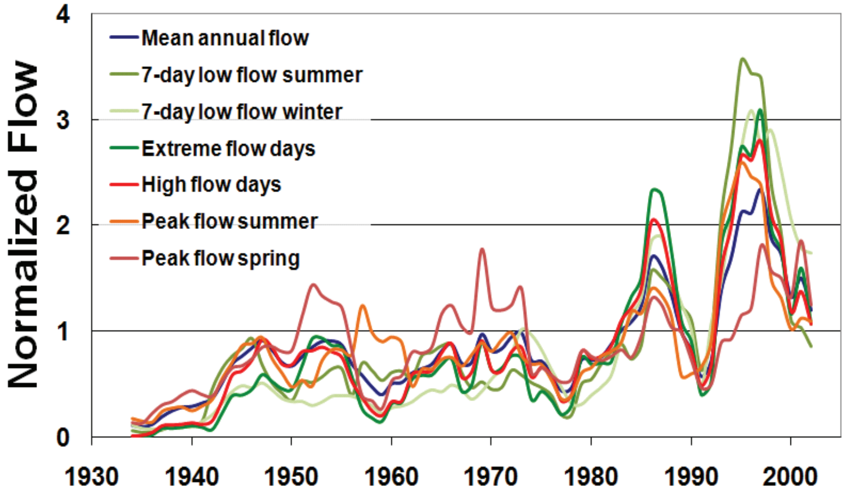

FIGURE 2-8 Seven streamflow characteristics in the Minnesota River basin, showing substantial increase in recent decades. Values are 5-year running averages normalized by 1950-2002 mean values. These changes involve a mix of variability on different time scales, suggesting multiple, intertwined causes. SOURCE: Modified, with permission, from Novotny and Stefan (2007). © 2007 by Elsevier.

changes are mostly amplifying natural change? How can early warnings of critical transitions or regime shifts be identified?

Not only is the causality of subtle shifts and regime changes in streamflow important, but understanding the environmental impact of changing streamflows is at the heart of predicting environmental changes. More frequent occurrence of high streamflows increases bank erosion and fine sediment delivery to streams, altering water quality and impacting aquatic life. Higher flows also incise streams, isolating them from their floodplains and reducing their capacity to absorb environmental stresses, such as removal of nitrogen and other nutrients. Similarly, altered frequency of low flows affects stream water quality, biogeochemistry, sediment transport, and river life. Understanding causes and patterns of changing hydrology is necessary for understanding changes in streamwater quality and aquatic life—posing new challenge frontiers at the interface of hydrologic sciences with sister natural sciences as well as with management and policy. Can human-induced hydrologic changes be regulated to minimize changes in stream ecosystem functioning? How are natural and anthropogenic changes modulating each other nonlinearly to amplify or dampen environmental change? Are high and low flows equally affected by human-induced changes, and how can change be understood as a function of both magnitude and frequency? Multiple stream processes combine to produce the net effect on water quality and aquatic life. What are the feedbacks among these coupled processes? Are some of these processes more sensitive to changing streamflow than others? Which ones are the most important to target for reducing negative impacts on water quality and aquatic life?

2.4. Timescales of Hydroclimatic Variability and Change

The climate system can vary at long time scales as well as shift rapidly into new modes of behavior that are radically different from the historical experience, resulting in large hydrologic changes.

Hydrologic processes are largely driven by climatic factors that vary over multiple time scales. Understanding of abrupt changes over short timescales and changes that vary over multidecadal to millennial and longer time scales is far from complete. The climate of the near and far distant past holds knowledge of causes and drivers of climate variations and their impacts on hydroclimate. This understanding is critical for generating future scenarios of hydrologic variability (e.g., runoff and recharge) that include both natural variability and human impacts on climate.

Slowly varying natural climate behavior is driven by similar conditions in the world's oceans and their interactions with the atmosphere. A number of recognized ocean-atmospheric circulation patterns appear to vary on decadal and longer time scales. Some of these are linked to known dynamics, such as ENSO, while the causes of others are less clear bur may be inherent, internal, ocean-atmosphere dynamics. Decadal variability in north Pacific Ocean sea-surface temperature interacts with ENSO, enhancing and diminishing its teleconnection effectiveness depending on phase. In the Atlantic Ocean, the Northern Atlantic Oscillation, a pressure seesaw between Iceland and Portugal's Archipelago of the Azores, appears to vary on both short and long time scales, while the leading mode of sea-surface temperature variability in the North Atlantic appears to vary on multidecadal time scales, possibly paced by the thermohaline circulation.

These interactions between the world's oceans and the atmosphere, whether the drivers are fully understood or not, have strong links to hydroclimate variability in many regions of the world. Developing a more complete understanding of these slowly varying influences is important for anticipating how climate change trends will interact with natural climate variability at long time scales. Because instrumental and gauge records are typically only 100 years long or less, paleoclimatic data are critical for developing this understanding.

The definition of abrupt climate change depends partly on context, but the committee adopted the following a generally agreed-upon definition:

> a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruption in human and natural systems (U.S. Climate Change Science Program, 2008).

These rapid changes in climate that affect the cryosphere and hydrologic variability present a number of challenges and research opportunities for the hydrologic sciences.

The impact of rapidly changing climate on hydrologic processes is greatly enhanced in regions where the cryosphere plays an important role in water storage. Abrupt events could lead to changes in the timing and volume of snow and icemelt in mountainous and polar regions where snow is an important component of the hydrologic cycle. If the large areas of permafrost (perennially frozen ground) thaw, then there may be an increase in discharge from polar rivers. A rapid disintegration or melting of glaciers, ice caps, and the major ice sheets in Greenland (Figure 2-9) and West Antarctica in response to warming could have major consequences for sea level. Recent estimates based on glaciological constraints suggest that a potential sea level increase of as much as 2.0 m is physically possible by 2100, but that an increase of ~0.8 m is more likely (Pfeffer et al., 2008). A rapid rise in sea level would not only inundate low-lying coastlines but also dramatically affect coastal aquifer systems and increase erosion even in areas where inundation is not a problem.

Other examples of abrupt change with critical impacts on the water cycle include extreme and protracted droughts and episodes of regional flooding. Both events are influenced by shifts in the ocean-atmosphere systems that control the delivery of moisture to a region. Drought that evolves more rapidly than can be accommodated by adapting human or natural systems, even if not permanent, can threaten the survival of societies and ecosystems. Drought can be prompted by changes in large ocean-atmospheric patterns of circulation, such as those generated by ENSO. A persistence of the cool phase of ENSO, which results in drought across much of the southwestern United States today, is hypothesized as a reason for the increased aridity in the western United States during the medieval period. The warm phase of ENSO can result in episodes of regional flooding, exposing societies and ecosystems to risk, in regions such as southern California and the states along the Gulf of Mexico.

FIGURE 2-9 Flowing meltwater on the surface of the Greenland ice sheet. Some of this water goes into the ice sheet through features called moulins, eventually reaching the bottom, where it may promote more rapid flow of the ice. Meltwater and moulins have been occurring at higher and higher elevations over time. SOURCE: Reprinted, with permission, from Roger Braithwaite, University of Manchester and Specialiststock.com.

How will future changes in the water cycle, influenced by human activities, take place in the context of slow but significant natural variations in the climate?

The Earth-atmosphere-ocean system is inherently complex, and ocean conditions vary relatively slowly (because of the rate at which water gains and loses heat) compared to the atmosphere. This results in climatic and hydrologic variability over a wide range of time scales, including the decadal to century scales that are critical to water resource decision making and infrastructure planning. Although human activities will impact the future trajectory, the low-frequency natural variability operating on interannual to centennial scales and longer will persist, underlying anthropogenic climate change (Figure 2-10). This low-frequency variability has the potential to either exacerbate or mitigate the impacts of human-induced trends, such as warming, on hydroclimatic variability and extremes. GCMs currently do not reproduce well the observed low-frequency variability, necessitating the use of both long records of natural variability and information from GCMs for plausible projections of future climate and hydrology.

ENSO is one of the best-understood, large-scale drivers of regional climates and hydroclimatic variability, and it influences climate in many parts of the world. Understanding of ENSO, which operates on time scales of roughly 2-8 years, had led to the ability to produce useful forecasts for the regions with the strongest teleconnections to ENSO. Other more slowly varying climate modes, such as the Pacific Decadal Oscillation, the Arctic Oscillation, and the Atlantic Multi-decadal Oscillation, are also known from the observational record. Couplings among these modes of variability for hydrologic processes are understood to some extent. For example, the low-frequency component of ENSO, commonly recognized as Pacific Ocean decadal variability (or the Pacific Decadal Oscillation, PDO), appears to reinforce or weaken the regional impacts of ENSO at decadal time scales. For regions that are not strongly or consistently affected by ENSO, the PDO, or other well-studied decadal variability, research is needed to determine other drivers of low-frequency climate variability. This includes the jet stream, as well as patterns of high and low pressure that set up and persist seasonally. Understanding and anticipating low-frequency hydroclimatic variability would allow for resource management and planning that take advantage of intervals of more favorable conditions to prepare for intervals that place more stress on resources.

In many cases, instrumental records of climate are too short to evaluate and investigate hydroclimatic variability at multidecadal and longer time scales. Paleoclimate data, particularly from tree rings and other high-resolution data, have proven to be valuable for reconstructing past modes of climate variability. In many cases, reconstructions of ocean-atmosphere

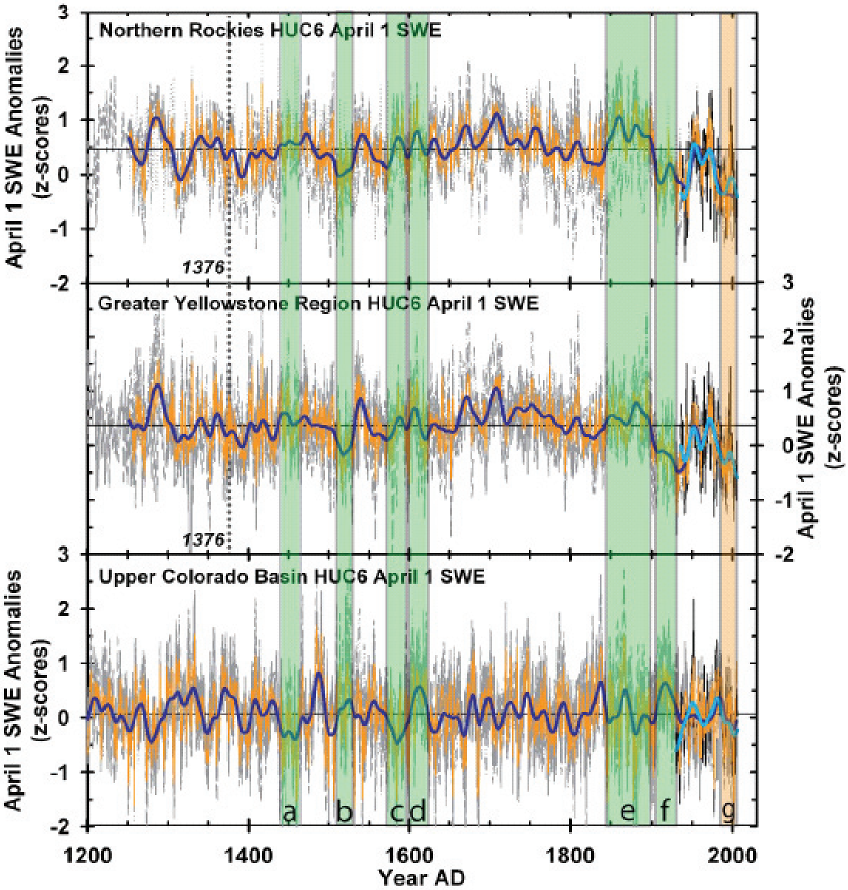

FIGURE 2-10 Reconstructions of snowpack in the northern and central Rocky Mountains from tree-ring data. The graphs of the April 1 snow water equivalent (SWE) reconstructions show multiple watershed reconstructions (gray lines) within each larger region, with the regional average (orange line), smoothed (dark blue line). For the Northern Rockies and Greater Yellowstone region, the reconstructions are most reliable after 1376 (dotted vertical line). The 20th-century records of observed April 1 SWE are also plotted for each large region (black lines) and smoothed (cyan line). Shaded intervals show decadal-scale SWE periods highlighted in the full paper. The observed and reconstructed SWE records are plotted as anomalies from the long-term average. These records indicate that wet conditions in the northern Rockies and Yellowstone region tended to coincide with dry conditions in the Colorado River basin over the past centuries. However, this natural variability at 20- to 50-year time scales has been more synchronous because of late-20th-century warming, resulting in a decline in snowpack across all three major watersheds. SOURCE: Reprinted, with permission, from Pederson et al. (2011). ©2011 by the American Association for the Advancement of Science.

circulation use land-based proxies that imply moisture transport from remote locations and have some utility. What types of paleoclimate data can be better exploited to indicate behavior for regions, such as the oceans, that are relatively data scarce? Notable features of past climate, such as the droughts of the medieval period, contain information that may be useful for anticipating the future, but understanding the global climate context for these droughts would be even more valuable. Can multiproxy records (records from multiple sources that document climate, such as tree rings, lake sediments, and ice cores) of past climate, along with climate modeling, be used to simulate global climatic variability and its drivers during anomalous periods, such as the medieval period? Much focus has been placed on the tropical Pacific Ocean variability, and with good reason, but is it possible to develop robust ensembles of paleoclimate reconstructions of modes of climatic variability in other parts of the world as well? Finally, how can paleoclimate data be best used to disentangle the low-frequency natural variability from trends due to climate change, and can this information be used to inform the range of hydroclimatic conditions that can be expected in the future?

Hydrologic systems, particularly the large reservoirs that contain water storage that equals several years of accumulated flow, may have different time scales of response compared to the combined effects of seasonal, annual, and multiyear climate variability. Low-frequency variation in hydroclimate superimposed on trends in temperature may affect the impact of drought in such managed hydrologic systems. Understanding the low-frequency variability and its impacts is critical for managing water supplies under a variety of scenarios. Can modeling be used to produce ensemble projections of hydroclimatic variables for use in water resource decision making? Some use has been made of paleoclimate data in assessing long-term reservoir operations under a broader range of conditions than that provided by the gauge records (e.g., Lower Colorado region, Bureau of Reclamation). How can these applications be expanded to use the low-frequency information in paleoclimate records, along with projections for future climate change, to present a plausible range of conditions?

What causes "tipping point" transitions of the climate and what are the hydrologic implications?

A tipping point with global implications is a transition from what is now occurring to an entirely new climate state or a point where abrupt climate change occurs. Earth's climate system has shown some evidence of regime behavior, most notably the potential to exist in at least two different states even with the same solar forcing, such as states with or without a thermohaline circulation. A shift in the climate regime from one state to another would have huge implications for many aspects of the hydrologic cycle, including the behavior of the cryosphere, surpluses and deficits in surface water reservoirs, and the frequency of extreme hydrologic events such as floods and droughts.

As climate models have become more complex, the spread of their projections of future climate has tended to widen, suggesting that increasing the number of processes included in the models reduces the predictability of the climate system. This also suggests that positive feedback processes not yet studied or modeled may amplify some fluctuations in the climate system. If the amplifications are large enough, they could push the climate system into new modes of behavior or induce an abrupt change. Furthermore, paleoclimate records have revealed past episodes of rapid change to new climate regimes. There is value in understanding the past frequency of such "abrupt" episodes and the processes that caused them, but this requires relatively long records. Refinement of records extending back hundreds to many thousands of years is needed to provide clarity on how natural processes, acting alone or in conjunction with human-caused factors, may yield rapid climate change in the future. Paleoclimate analyses that document abrupt climate change under natural climate variability (Overpeck and Cole, 2006) coupled with improved hydroclimate modeling will provide insights into causes and consequences of climate transitions and their hydrologic implications. Because models likely do not contain the feedbacks that trigger tipping points that are documented as abrupt changes in the paleoclimate record, scientists still lack the information needed to understand and anticipate tipping point transitions. What modeling improvements and paleoclimate data are needed to understand and project potentially catastrophic abrupt changes in a warming climate?

2.5. Exohydrology

The presence of water in and on planets changes everything—from deep interior dynamics to the surface evolution of landscapes to the potential for life.

The recent exploration of Mars has popularized the idea of "following the water" to look for life on other planets. Life occurs nearly everywhere on Earth's surface and, surprisingly, microbial life may occur even deep in Earth's wet underlying bedrock, perhaps as much as 5 km into the igneous rock underlying the oceans. There may even be more biomass in this deep rock reservoir than in the overlying oceans and on the entire land surface.

Of course Earth is a water planet, with 71 percent of its surface area in oceans. Earth is blanketed in a watery atmosphere and washed by rainstorms and snowmelt. What is less appreciated is that the dynamics and composition of the entire *solid* planet are affected by the distribution and abundance of water. There is a deep water cycle. The motion of mobile plates of crust that collide, creating mountains, and separate, making ocean basins, depends on water in the underlying mantle (with some of that water coming from subduction of wet ocean slabs). Water deep in the planet affects its chemical evolution and its internal dynamics. The abundance of granite on Earth records the extensive mixing of water with basalt and other rocks. The nature of volcanic eruptions and the movement of faults are strongly influenced by water. Ultimately, water weathers bedrock, and erodes, transports, and deposits mass, some of which is subducted with the ocean floors and enters the mantle. Hence, the water cycle, including the deep water cycle, strongly influences the composition and dynamics of the planet and likely the same is true on other water-rich planets (Marcy, 2009).

When society explores other planets, then, a key goal is to quantify the abundance and dynamics of water, not only to determine the possibility of life elsewhere but also to understand how the entire planet operates. The recent discovery of planets beyond the solar system has led to new models of the positioning of planets and their size and composition relative to their sun. The presence of water is central to predicting the composition and dynamics of these planets, as well as to the potential for "habitability."

The study of hydrologic processes on other planets could be termed "exohydrology" and it is only just beginning. As a sign of the current importance of this topic, the American Geophysical Union convened a session at the fall 2011 meeting titled "Follow the Water: Insights into the Hydrology of Solar System Bodies." There is also a literature developing on exohydrology (e.g., Andrews-Hanna and Lewis, 2011). Although exohydrology is necessary to understand the evolution and climate of other planets, it also offers a test of the understanding of how Earth works. Abundant new imagery has presented startling observations of river channels, alluvial fans, gullies, and deltas on a planet where surface liquid water is currently absent (Mars) and channels, lakes, and rain driven by condensing and evaporating methane (Titan). The committee suggests two important research questions that focus on surface water processes. These questions present challenges that are ripe for interdisciplinary research between hydrologic scientists, paleohydrologists, planetary scientists, and geomorphologists in exohydrology.

What are the definitive signatures of rain and surface water transport on a planetary surface?

Is there is a unique relationship between surface morphologic features and the mechanism that formed them, and if so can hydrologists specifically assign a role to water? On Mars, channels that originate near drainage divides (the tops of ridges) suggest that, in the past, the planet had an atmosphere capable of producing precipitation (rain or snow). Can geomorphic features give us such unique interpretations? For example, how do hydrologists distinguish gullies formed by dry avalanches versus wet debris flows versus bedload transport in surface water flows? Early in the manned exploration of Earth's moon, satellite imagery revealed sinuous channels (also called rills). These channels are broadly distributed across the Moon and show morphologic features quite similar to river channels found on Earth. The first papers on these new observations proposed that they were possibly formed by meltwater from permafrost. Subsequent landings on the moon revealed that channels were formed by flowing lava. Sinuous rills, which possess morphology similar to river channels, have been mapped on Venus, likely formed there by flowing lava. On Titan sinuous channels and valley networks show great resemblance to features formed by flowing water, but in this case scientists can be certain that the fluid is not water but most likely methane. Despite the abundance of features on Mars that bear very strong resemblance to terrestrial water-driven landforms such as outburst channels, alluvial fans, and deltas, debate continues about the abundance, origin (rain, snowmelt, or spring flow), and necessity of surface water.

What is the role of water in creating specific landforms? Although scientists have the advantage at times of seeing geomorphic processes occurring on Earth, they more often have only the resulting morphology to interpret. Hence this research, while motivated by planetary questions, also has bearing on the understanding of landforms and what they reveal about processes. What are the distinguishing metrics and mechanistic theory that can yield these insights?

Is it possible to estimate the magnitude, duration, and frequency of surface waters (river channel flow, springs, lakes, and oceans) from morphologic evidence alone?

This question, which emerged with regard to Mars after the discovery of so many compelling, potentially water-driven features, applies equally to Earth and other planets. Perhaps the clearest example is the problem of how to extract such information about flow from a simple river channel. If scientists had data on channel plan form, cross-section, slope, and even bed material grain size (much more difficult to obtain on other planets), then what can be said about the flows that the channel experiences? Sedimentologists viewing preserved channels in the stratigraphic record push even further and ask what can be said about the drainage area and sediment supply the channel carried. These questions are central to the field of paleohydrology and, in general, to the understanding of the relationship between flow characteristics and channel morphology.

With sufficient topographic and grain size information, a calculation of the flow that just fills a channel (bankfull flow) can be made with reasonable accuracy. This is widely practiced on terrestrial channels and on Mars. But what clues are there about how long the bankfull flow lasts, how often it occurs, how often much larger flows occur, and whether there could be sustained low flow? Empirical studies of direct measurements of terrestrial channels provide some data. How can such findings be extrapolated to other planets and, importantly, to other ungauged channels on Earth? The prediction of flows in ungauged basins has generally relied on some mixture of empirical characterization of regional runoff characteristics and quantitative measures of basin properties (e.g., channel network structure). These methods typically require data on precipitation, whereas on other planets, the question being asked is, from channel morphology (and perhaps basin characteristics) can scientists estimate the amount of precipitation needed to create that morphology?

These questions point to another gap in the knowledge of terrestrial hydrogeomorphic processes. Is there a climatic signature in river morphology? For example, other factors being equal, will channels primarily fed by snowmelt differ significantly from those experiencing only rare monsoonal runoff events? This question has received little attention, yet lies at the heart of understanding of how river morphology records hydrologic processes. Progress on these questions about terrestrial hydrology and morphology will greatly inform exohydrology studies.

CONCLUDING REMARKS

The aspects of the water cycle highlighted in this chapter present numerous scientific challenges, from understanding the near-surface flux terms foundational to Earth's metabolism and the global-scale natural drivers of hydroclimatic variability, to extending lessons learned on Earth throughout the universe. These are among the most important of the wide range of water cycle topics. Recent advances in observing, measuring, analysis methods, and modeling make addressing many of these challenges attainable. Pairing these new advances with scientific challenges is a critical component of accounting for and predicting the human footprint on Earth's water cycle. For example, the coupling of modeling and observational advances could allow for continuous, regionally detailed monitoring and prediction of water-cycle dynamics, with forecasting times and accuracy extending ever further into the future, potentially on interannual and longer time scales. Modeling advances could also allow for simulation of alternative scenarios for water's future in a climate system that includes socioeconomic as well as natural controls on its movement.

Finding solutions to the questions presented here requires research along the traditional lines of hydrologic sciences to, for example, promote scaling theories. Yet this effort also requires interdisciplinary research in relatively new disciplines such as hydroclimatology and paleohydrology. Entirely new disciplines, for example, exohydrology, will also generate new thinking and activity to further understanding. Field studies, whenever feasible and appropriate, are important.

As the committee noted in the beginning of this chapter, water does not respond passively to physical processes governing Earth: it is a dynamic agent whose influence is central to processes that produced the world as society knows it and that will affect its evolution into the future. Water is locally exhaustible, which is why it is critical to understand its dynamics. Moreover, human intervention in the water cycle alters water's role on the planet. All of the phases and states of the water cycle are linked, and impacts of human activities on one component of the hydrologic cycle are consequently circulated to other components. This chapter focuses on the water cycle, but the next two chapters will revisit the water cycle as the component that integrates water throughout all biological and Earth systems. Chapter 3 extends this discussion beyond the processes that were addressed above into a host of ecohydrological topics.

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3

Water and Life

Water and life are inseparable and interacting. Ecosystems depend on and drive hydrologic processes, giving rise to distinct patterns of biotic communities, and a climate system strongly coupled through vegetation to moisture in the ground.

INTRODUCTION

The evolution of life on Earth likely began with the formation of liquid water and has been shaped by the flow of water ever since. Water is essential for all living organisms, and, on land, the magnitude of water supply and the timing of water delivery structures biological systems at all spatial and temporal scales. Over geologic time scales, hydrologic change has been a major force of natural selection. Across modern Earth, annual precipitation and temperature explain much of the variation in the stature and composition of vegetation, and the pattern of hydrologic connections constrains the distribution of many organisms as they migrate to complete their life cycles.

Although the amount and timing of water supply ultimately constrains life on Earth, living organisms collectively influence the water cycle and the global climate. Vegetation blankets the majority of Earth's land surface, altering its albedo (reflection of solar energy), recycling its water, and mediating its gaseous and aqueous chemistry. Biotic communities directly alter landscape properties (such as topography, permeability, weathering geochemistry, and erodability), fundamentally changing soil formation, erosion processes, runoff paths, river morphology, and in turn the water and nutrient availability that sustains biotic communities. The currency of these interactions, which take place over molecular to global scales, is water.

Recently ecologists, geomorphologists, biogeochemists, soil scientists, and hydrologic scientists have found that a common frontier of their fields lies at the nexus of life and water. New cross-disciplinary research is emerging with a surge of literature already illuminating progress and ways forward and applying disciplinary names such as ecohydrology, ecological climatology, and hydroecology. One measure of this surge is the increased frequency of published articles using the terms ecohydrology and hydroecology, terms that weren't widely used prior to 1990. Today, a Web of Science search for these terms shows the growth of these interdisciplinary publications over the past 20 years, with the majority of that growth taking place from 2000 to the present. The breadth, strength, depth, and importance of this topic—the co-action of life and water on Earth—ensures that the great opportunities for discovery will be pursued.

RESEARCH OPPORTUNITIES

This chapter discusses six research topics and associated exemplary questions. The topics are not meant to be exclusive but are among the most important in the subject area. The central theme is the idea of bidirectionality (i.e., water affects life, which affects water). This interaction can be over a short time period of, e.g., a growing season, or over geologic time in which evolution occurs. Studies suggest that action at the finest scale, such as the controls on moisture availability to root hairs, can have consequences for the large scale, such as regional climate. Hence, local mechanistic understanding is needed, and therefore the significant challenge of upscaling should be tackled. Interactions can lead to patterns, from repeating patches of vegetation to the self-organized development of ridge-and-valley topography. Such patterns invite theory, and these two patterns in particular have driven much research. The coupling, bidirectionality, and internal dynamics of these patterns can lead to a high sensitivity to change and to the potential for irreversible change (e.g., see D'Odorico and Porporato, 2006).

3.1. Deep Time Landscapes

Landscapes, hydrologic processes, ecosystems, and climate have co-evolved throughout Earth's history and across all spatial scales.

Early Earth history is nearly as mysterious as the geologic evolution of other planets. To inform understanding of early Earth, scientists have limited preserved bedrock, some chemical records, and scant fossil evidence. Nonetheless, early life clearly interacted with the physical system. The fossil record suggests that as the evolution of life exploded and proceeded, the fossil record points to evolutionary inventions that altered how the planet works. Much is yet to be learned.

How have hydrologic processes affected the co-evolution of life and planet Earth?

Although a finite set of hydrologic processes are involved in Earth's water cycle, the relative rates and importance of the processes have changed dramatically throughout Earth's history. These changes corresponded and contributed to major evolutionary steps in emergence of landscapes and their ecosystems and the climate system (including the oceans). Three examples illustrate this point.

Early Earth is a great puzzle. The early Sun was 70 percent as bright as today (Kasting, 2010), and consequently the Earth should have been a frozen sphere for nearly one-half of its history. Instead geologic evidence makes it clear that oceans were present very early, and it is possible that Earth was even warmer than present. But then, approximately coincident with the rise of atmospheric oxygen from photosynthesis, the first known global glaciation occurred approximately 2.4 billion years ago. Since then Earth has periodically experienced "ice house" conditions of large-scale glaciations. Numerous hypotheses explain the "faint young sun" puzzle, but three-dimensional climate simulations that explicitly account for hydrologic processes of runoff, storage, and evaporation must be developed to fully explore them.

Another puzzle for hydrologic science arises from the "snowball Earth" event about 650 million years ago, during which it has been argued that much of Earth's ocean and terrestrial surface was covered with ice. This event is of particular interest because its termination was marked by an explosion of multicellular life, known as the Cambrian explosion. Why did Earth's water freeze and then thaw? There was also a significant rise in oxygen after the snowball Earth period ended. Recently it has been proposed that this rise in oxygen resulted from accelerated erosion of high mountains that flushed nutrients to the sea, greatly increasing photosynthesis. These events highlight the need for further understanding of the relationships among climate, topography, hydrology, erosion, and ecosystems.

Perhaps the most radical change in hydrologic processes after the emergence of continental landmasses was the evolution of land plants and the subsequent diversification of terrestrial life. Terrestrial organisms permanently changed hydrologic processes in at least two fundamental ways. With the development of stomata, about 400 million years ago, plants could lift water from deep soil reservoirs without desiccation and transfer it back to the atmosphere, greatly increasing this mass flux (Figure 3-1). This acceleration of the hydrologic cycle profoundly affected climate processes. The spread of vegetation and fauna across landscapes led to more intense weathering and the development of deeper conductive soils, which must have systematically increased near-surface storage of water and brought

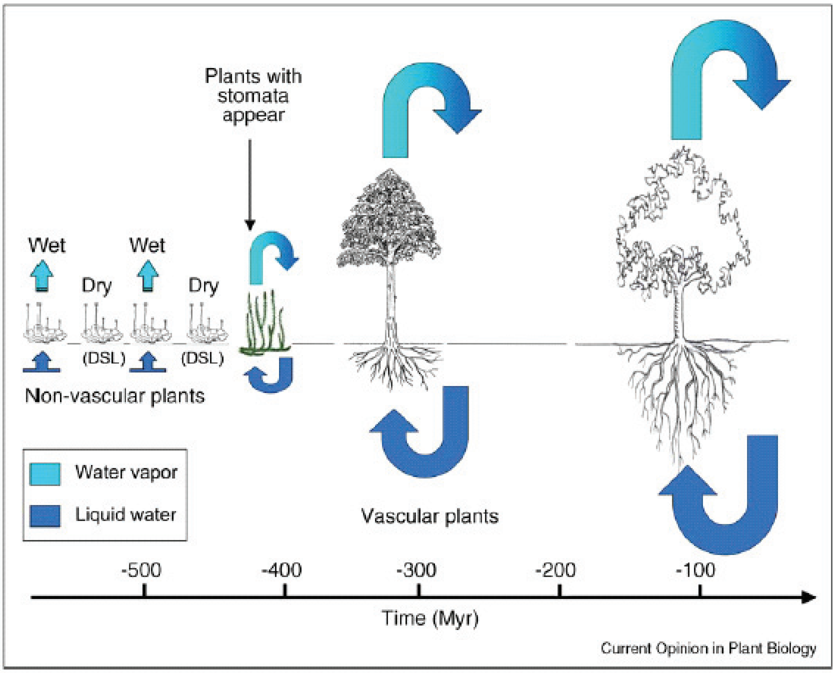

FIGURE 3-1 The evolution of roots, vascular tissue, and stomata through the Devonian Period permitted plants to gain access to water stored deeper in the soil and to transfer it into the atmosphere. This increase in transpiration generated increases in precipitation over continents, significantly influencing the water cycle and climate processes. SOURCE: Reprinted, with permission, from Berry et al. (2010). © 2010 by Elsevier.

about a dominance of subsurface flow to river channels for much of the global runoff that reaches channels. Erosion processes and rates also must have changed, altering landscape evolution. All current landscapes and ecosystems emerged under this new, biologically mediated hydrologic system. More focused research is needed to understand how the hydrologic feedbacks between organisms and the physical environment shape the coevolution of landscapes, and the extent to which vegetation controls hydrology at local and regional scales.

3.2. The Hydrology of Terrestrial Ecosystems

Hydrology plays a critical role in driving the environmental patterns that exist and evolve on Earth.

Dominant vegetation type or biomes, standing biomass, and annual primary production (energy fixation from sunlight by plants) vary with mean annual precipitation. Within biomes, inter- and intra-annual variation in the timing and amount of precipitation can exert strong control on primary productivity and vegetation structure. In systems where vegetation growth is strongly water limited, small changes in the magnitude and timing of precipitation can lead to dramatic changes in vegetation composition and productivity. These interactions are less obvious, but no less important, in more humid, nutrient-limited ecosystems, where the amount, timing, and routing of water supply can substantially affect nutrient availability and soil carbon storage.

Across the full gradient of annual precipitation, the key link between the biosphere and the hydrosphere is soil moisture. Soil moisture fuels bare-earth evaporation and plant transpiration. Yet, evapotranspiration and soil moisture dynamics are the two primary unknowns in water budgets of landscapes. Soil moisture dynamics drive soil respiration (the flux of carbon dioxide, CO_2, from the soil to the atmosphere) and are a significant contributor to the global CO_2 budget, but soil moisture has proven extremely difficult to predict. Climate models that find agreement in predicting future temperatures and rainfall may nonetheless generate widely different predictions of soil moisture. Reducing this critical uncertainty in understanding the mechanisms of feedbacks between vegetation and climate is central to the ability to effectively predict future climate and vegetation dynamics at local and global scales.

Among the barriers to building meaningful predictions of soil moisture are the challenges to linking small-scale transport processes in plants and soils with local atmospheric processes. In a review article, Katul et al. (2007) suggest that two primary barriers limit the progress of soil-plant-atmosphere interactions mediated primarily by hydrologic fluxes. First, scientists have limited ability to describe water movement at the very smallest scales where fine plant roots interact with soil water, where small tubes (xylem) carry water in plants, and where water diffuses through plant tissue. Second, once scientists achieve appropriate microscopic descriptions, the appropriate methods to extrapolate them to larger spatial scales and longer time scales are lacking (what is known in the field as an "upscaling" problem). Understanding how water molecules move through soils and plant tissues and developing the scaling laws necessary for extrapolating this understanding to ecosystem scales is a challenge.

Hydrologists have made significant progress in understanding how vegetation responds to and controls local and regional hydrology in arid and semi-arid climates, where water limitation is a major determinant of vegetation patterns. Here competition for limited water leads to spatially structured vegetation, which may simply trace the topographic controls on water paths. Alternatively, plants themselves may create spatially variable conditions favorable to their survival by influencing soil characteristics that alter surface water infiltration, moisture retention, and erosion. Much remains to be discovered about controls on pattern and process.

Hydrologists, ecologists, and geomorphologists have found common cause in studying the water mediated interactions among climate, vegetation, and landscapes within terrestrial ecosystems. These ecosystems include the entire food web of animal life they support, but the dependency of animals on precipitation is often indirect and tied to precipitation variability and seasonality. In water-limited landscapes, correlations between ungulate populations (for example) and rainfall have been found, but even here density-dependent interactions, such as competition for food, may obscure simple climate dependencies (Owen-Smith, 2006). Understanding how the loss of native species or the addition of invasive species to ecosystems may alter vegetation and climate is equally important as understanding how changing climates may affect terrestrial organisms.

How do soil and rock moisture vary across landscapes and in turn drive biotic, geochemical, erosional, and climatic processes?

Water in unsaturated soils, typically referred to as soil moisture, is returned to the atmosphere through bare soil evaporation and plant transpiration. This evapotranspiration is approximately 57 percent of the total land precipitation (Van der Ent et al., 2010), and it uses up about 50 percent of the total solar energy absorbed by the land surface (e.g., Seneviratne et al., 2010). Soil moisture influences climate as a source of moisture, and in various ways it influences latent and sensible heat fluxes. Soil moisture influences water potential gradients (and thus infiltration rates and unsaturated subsurface flow rates), thereby influencing runoff paths and the resulting erosion during storms. Geochemical reactions are partially paced by water content and associated microbial activity. Soil moisture controls and is regulated by vegetation; hence, understanding moisture dynamics is central to related studies. Soil respiration varies with seasonal moisture in the soil. Despite the central role that soil moisture plays in Earth surface processes and ecosystems, the spatial and temporal dynamics of soil moisture are poorly documented, and theory predictions have had limited success.

Hydrologists have played a leading role in mapping soil moisture and developing theory about its distribution across landscapes. Remote sensing technology for mapping moisture dynamics, while providing valuable observations, only penetrates a few centimeters into the ground. Therefore, field observations and theory remain essential to obtaining estimates of soil moisture patterns and dynamics. Ground-based technology for mapping soil moisture to significant depths is advancing and will be important in creating field data sets to test remote sensing and model-based predictions of soil moisture dynamics. For example, naturally produced neutrons and their thermalization are utilized in the Cosmic Soil Moisture Observing System[1] (COSMOS) to provide larger footprint measures of soil moisture (Zreda et al., 2008). Distributed temperature sensing (DTS), in which optical fibers are "planted" across agricultural fields at varying depths, is now providing soil moisture estimates using either the natural diurnal heat flux within the shallow soils, or by actively heating the cable over its entire length to form an enormous heat dissipation sensor. New approaches for assessing both the spatial and depth distribution of soil moisture are beginning to fill the gap between point sensors and remote sensing, yet this major data gap remains. Climate models are beginning to reach a resolution where the topographic effects on moisture redistribution can be treated. Large differences remain in how such models treat the water holding capacity of soils and how soil moisture regulates evapotranspiration. What are the effects of topography, geology, and land history on soil moisture patterns and dynamics?

Field studies of rooting depth of vegetation, direct observation of water transport in roots, and results from climate modeling all point to the importance of deep water sources (several meters below the ground surface). Sufficiently deep roots can lift deeper water to near surface soils, increasing moisture availability to shallow roots. In some places, soils are thick and can provide this deep water, but in others, especially places underlain by bedrock, the moisture available to plants may reside in the underlying fractured rock. In seasonally dry, hilly landscapes with thin soils, vegetation may be sustained by moisture extracted from weathered bedrock beneath the soil. The importance of this so-called "rock moisture," and the groundwater that lies beneath it, in providing water to vegetation is relatively unexplored.

To improve hydrologic, climate, geochemical, and ecological models, field observations and theory are needed to explain and predict the spatial variation in the thickness and properties of the soil mantle and the underlying conductivity of weathered rock across landscapes. Climate models rely on compilations of soil thickness and texture properties extracted from soil surveys, but as the finer-scale topography of hills and valleys enter into climate models, soil data spatially mapped onto this topography will

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[1] See http://cosmos.hwr.arizona.edu/.

be needed. Very little is known quantitatively about this mostly invisible mantle, especially with regard to the spatial variation in depth of weathering of bedrock across landscapes. Although soil maps can provide guidance to estimating soil properties, there are no comparable data to estimate the depth of weathered rock that may serve as a moisture reservoir. Recently the zone from the canopy top through the soil and down into the underlying weathered bedrock and groundwater has been referred to as the "Critical Zone" (Box 3-1). Six Critical Zone Observatory field projects are currently

BOX 3-1
Critical Zone Observatories

In 2001 the National Research Council report *Basic Research Opportunities in Earth Science* (NRC, 2001) proposed the term Critical Zone to describe "the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources." The report recommended "integrative studies" of the Critical Zone as one of six "important problem areas spanning a wide range of future activity in Earth science." This challenge was embraced by the research community, and by 2007 the National Science Foundation (NSF) funded three Critical Zone Observatories (CZOs) for an initial 5-year investigation and subsequently added three more in 2009. This effort has inspired a corresponding program in Europe referred to as SoilTrEC (Soil Transformation in European Catchments)[a] and rapidly expanding international collaborations across the globe.

The CZOs are envisioned as field environmental laboratories to explore the chemical, physical, and biological processes that shape Earth. The three main goals are (1) to develop a unifying theoretical framework of Critical Zone evolution that integrates new understanding of coupled hydrological, geochemical, geomorphological, and biological processes; (2) to develop coupled systems models to predict how the Critical Zone is driven by anthropogenic effects, climate, and tectonics; and (3) to develop an integrated data-measurement framework to document processes and test hypotheses.[b]

The six established CZOs are located in (1) the Southern Sierra (California), (2) the Jemez River and SantaCatalina Mountains (New Mexico and Arizona), (3) Boulder Creek (Colorado), (4) the Susquehanna Shale Hills (Pennsylvania), (5) the Christina River basin (Delaware and Pennsylvania), and (6) the Luquillo Mountains (Puerto Rico). Each of these CZOs is managed by different multidisciplinary teams, and the mix of sites offers opportunities to explore different aspects of the Critical Zone. These CZOs form a national network and meet, coordinate, and collaborate as a shared program.

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[a] See http://www.soiltrec.eu/.

[b] See http://criticalzone.org/.

funded by the National Science Foundation (NSF) across the United States, wherein hydrologic processes and development of the soil and weathered bedrock zone are studied intensively in conjunction with biogeochemical and geomorphic processes. How can results of local mechanistic studies of soil and weathered bedrock be upscaled to watershed hydrologic and regional climate models?

How have vegetation assemblages, landscapes, climate, and the hydrologic systems that drive them co-evolved?

We live on a patterned Earth. Across the planet, vegetation is banded into distinct bioclimatic zones of differing dominant vegetation. Within a zone, topography and geology can drive moisture, slope stability, and soil and mineralogical differences that structures vegetation assemblages. Systematic differences emerge with respect to orientation of hills (i.e., aspect), with, for example, more forested, moisture-demanding vegetation facing north in northern latitudes (Figure 3-2). The visible co-organization of vegetation and topography, in which topographically structured moisture availability drives dominant vegetation assemblages (most prominent in water-limited environments), has attracted many researchers. These patterns are being examined at least three ways: (1) how vegetation patterns are driven by water stress, (2) how vegetation patterns may be used to document water availability and transpiration, and (3) how vegetation patterns may, in turn, affect hydrologic and erosional processes, thereby altering soil and topographic evolution.

Highly structured vegetation patterns also occur that do not correspond to strong topographic and soil control but, instead, are argued to be emergent features that arise from competing effects of facilitative and competitive processes within the vegetation community. In some cases remarkable vegetation patterns of repeating bands, spots, and mosaics develop. In water-limited environments where overland flow occurs, vegetation clustering can have such facilitative effects as inducing water infiltration, trapping nutrients, providing shade, and protecting against herbivory. A considerable body of theory has been advanced to predict these self-organized emergent vegetation patterns. The challenge is to provide definitive tests of the theory. The vegetation patterns themselves—without extensive field work to confirm driving mechanisms—may reveal very little about their origin and therefore provide an insufficient test of theories.

A frontier area of research is to expand these inquiries into humid regions where spatially structured water availability is less apparent, but vegetation patterns still form (Rodriguez-Iturbe et al., 2007). Fire pattern and history may strongly dictate vegetation patterns in both arid *and* humid landscapes, either emphasizing or obscuring water availability differences

FIGURE 3-2 Digital image of the Gabilan mesa area, south of San Francisco, California, showing the strong aspect control on forest distribution. Image is derived from airborne laser swath mapping data collected by the National Center for Airborne Laser Mapping (NCALM) and then colorized and shaded to reveal patterns of vegetation and topography. The distance between each valley is approximately 160 m. SOURCE: Reprinted, with permission, from Ionut Iordache, NCALM, and Whipple (2009). © 2009 by Nature Publishing Group.

and other disturbances (e.g., extreme storms, grazing, insect outbreaks, and invading species) can take significant roles. The inclusion of multispecies, food-web, and disturbance-driven processes in coupled models of climate, hydrologic, and vegetation pattern development is an area of expanding and exciting research. What are the hydroecological interactions that reinforce the spatial patterns across diverse landscapes and varying hydroclimate regimes?

All landscapes and their ecosystems have experienced climate change. Some systems may currently be legacies of a previous climate state under which they became established and now exist with limited resilience to further change. Ecosystems, hydrologic processes, and regional climate can co-evolve to create a self-sustaining system, but one that if disturbed may not recover. Perhaps the most important such system on Earth is the Amazon rainforest. A significant fraction of all terrestrial evaporation (and transpiration) is returned as precipitation over land (e.g., Van der Ent et al., 2010). Some argue that wholesale cutting of the forest or the effects of global warming could disrupt the self-sustaining hydrologic cycle of the Amazon, leading to widespread soil drying and a shift from mesic (having a moderate supply of water) forests to drier grasslands. Scientists need to understand how modern hydrosphere-biosphere feedbacks, like those in the Amazon, have evolved to maintain current vegetation patterns in order to anticipate future states. How will vegetation communities and their regional climate co-evolve with climate variability and change?

Landscapes evolve as channels erode down, steepening adjacent hillslopes, which, through this connection, may eventually develop a form that erodes at a rate similar to that of the channel. The competition of advective processes driven by runoff (which tend to predominate in channels) and diffusive processes (which tend to predominate on hillslopes) can lead to a regular ridge-and-valley topography with distinct wavelengths (Figure 3-2). Nearly all landscapes evolve under a biota mantle, yet explicit accounting for the effects of vegetation (or the assemblages of biota in the soil) in geomorphic models is just beginning. Do topography, vegetation (and their animal ecosystems), and the hydrologic processes that connect them co-organize over geomorphic time scales?

How can scientists predict abrupt change in terrestrial ecosystems?

Of great concern is the possibility that future state changes may be irreversible, and that the approach to state changes will be nonlinear or abrupt and thus very difficult to predict. The tight feedbacks between vegetation and climate set the stage for the potential for rapid transitions in vegetation dynamics. As global and regional climate changes, vegetation will both respond to and affect the climatic regime. Global climate models predict increased interannual variability in precipitation and more frequent extreme droughts, which may lead to dramatic changes in vegetation structure and productivity. The sustained drought that began at the turn of the millennium in Australia ("the millennial drought") is estimated to be the worst drought in the region in the past century (Nicholls, 2004) and has led to soil salinization and salinity induced tree mortality (Figure 3-3A). Recent droughts in the southeastern United States and warm summers in Alaska have dried out coastal plain and boreal peatlands, increasing their susceptibility to lightning-caused fires (Figure 3-3B). In 2009, an unprecedented peat fire in the Arctic released enough carbon to offset the annual carbon sequestration potential of the entire Arctic tundra biome (Figure 3-3C).

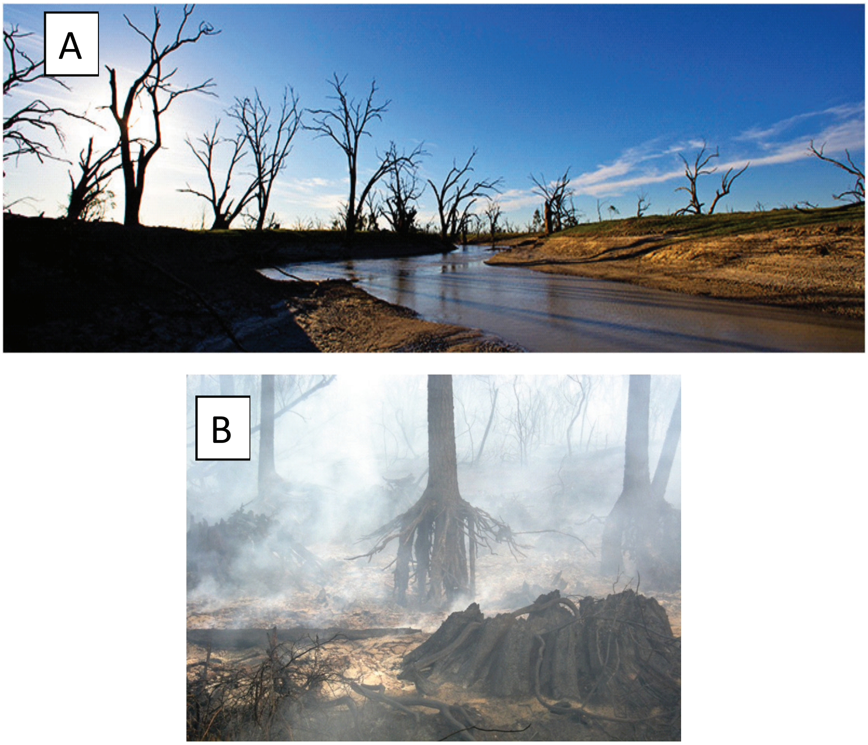
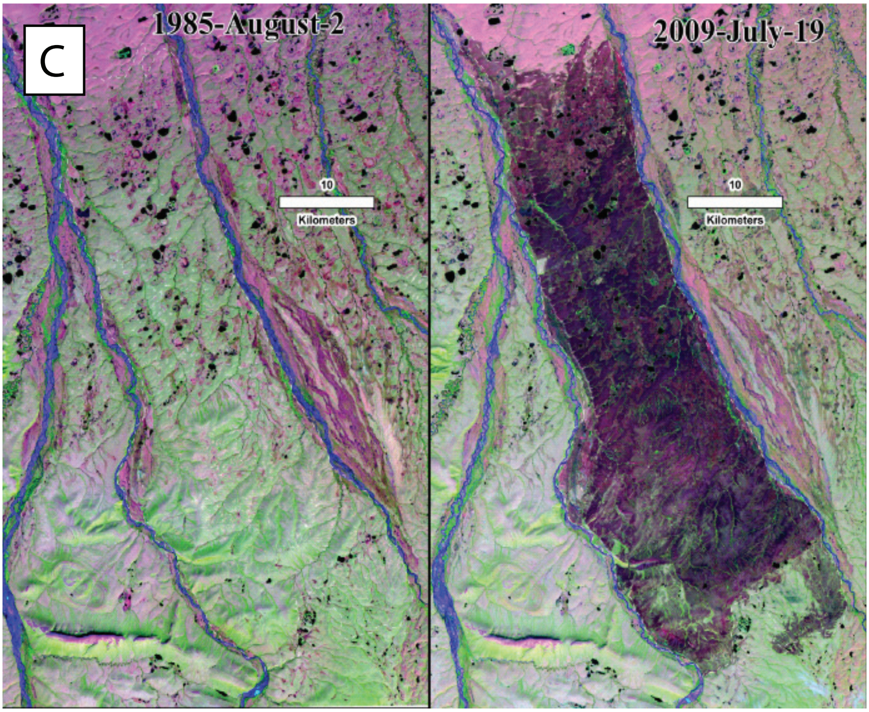


FIGURE 3-3 (A) The skeletons of red gum trees line the shrinking shores of Lake Pamamaroo in New South Wales. SOURCE: Reprinted, with permission, from J. Carl Ganter, Circle of Blue. (B) Smoldering peat in the 2008 fire in Pocosin Lakes National Wildlife Refuge, North Carolina in which 40,704 acres of peatlands burned over 6 months. SOURCE: USFWS (2009). Available online at http://www.

Conversely, changes in vegetation can strongly influence local climate, and particularly large scale changes when land cover can influence regional climate. Afforestation efforts can lead to dramatic reductions in streamflows, which may be proportionally more important in arid regions (e.g., Farley et al., 2005). Significant forest regrowth in the eastern United States has led to reduced midsummer temperatures in some areas. Conversion of native vegetation to croplands typically increases evapotranspiration rates and enhances cooling. Biological soil crusts, composed of soil particles and various microorganisms including cyanobacteria, green algae, and bacteria, are estimated to be the dominant ground cover in some arid lands. Destruction of these crusts through land management practices, especially grazing,



fws.gov/fire/news/nc/evans_road.shtml [accessed August 6, 2012]. (C) Landsat TM image of a large peat fire in the Arctic in 2009, pre and post scar. It is estimated that this fire released 2.1 Tg of carbon to the atmosphere. SOURCE: Reprinted, with permission, from Mack et al. (2011). © 2011 by Nature Publishing Group.

can lead to changes in runoff and increased erosion (including contributing to atmospheric dust loads). Land cover change can therefore strongly influence local and regional hydroclimatology. Incorporating the potential for abrupt changes in vegetation climate feedbacks into future climate modeling scenarios is an important research challenge.

3.3. Subsurface Ecosystems and Hydrologic Processes

Subsurface ecosystems create and direct hydrologic pathways, release gases to the atmosphere, and control access to moisture and nutrients by aboveground ecosystems.

Although largely invisible, subsurface ecosystems play a central role in hydrologic, climate, and aboveground ecologic processes. Soil formation is not only driven by the action of water movement and freeze thaw action, but also by biotic activity, from burrowing by worms, insects, and animals to geochemical processing by pervasive and extremely diverse microbial organisms. Soils, to a large degree, are a biofilm mixed with inorganic rocks and minerals that provide a key membrane on Earth's surface. Fauna and flora extend deeper into weathered bedrock, but here geochemical influences are more significant than mechanical disturbance by biota. Subsurface ecosystems, although concentrated near the surface where there are nutrients and high moisture levels, run deep.

Research has focused on the coupling of aboveground and belowground ecosystems. Roots make a direct connection between the two domains, and, despite considerable work, chemical, physical, and ecological processes associated with root interaction with the soil and the uptake of nutrients and water are still relatively poorly known. The flux of CO_2 from decomposition (respiration) is estimated to be more than 25 percent of the global CO_2 budget (Houghton, 2007). The flux comes from respiration by live roots, respiration from root symbionts exploiting root-derived carbon, and soil fauna respiration in consumption of soil organic matter. The relative importance of these processes is not well known, yet it matters in anticipating how CO_2 budgets will change under future climate states. Soil moisture influences subsurface biotic activity and thus the CO_2 flux. Water-driven subsurface ecosystem dynamics matter to global-scale processes.

Subsurface life—bacteria, fungi, and vascular plants—are affected by and also strongly influence hydrologic pathways and properties. Infiltration rate, hydraulic conductivity, and moisture retention properties all depend to some extent on biotic activity. Bacteria change the fabric of soils through their metabolic activities. Fungi, plant roots, and burrowing worms alter soil structure, thereby changing its hydraulic properties. Plants in arid regions establish in patches that alter sediment accumulation and water infiltration. Strong and important feedback mechanisms link hydrologic science, soil science, and ecology. Models that explicitly account for biotic activity will allow for better predictions of soil evolution and expansion of the understanding of related hydrologic and biologic interactions in the subsurface.

How are subsurface biota controlled by and influencing hydrologic processes?

The estimates vary, but there is general agreement that more life is below Earth's surface than above it. The diversity is staggering: just a few grams of soil could contain more than 10^{12} bacteria, representing more than 1,000 species, hundreds of species of invertebrates (Wardle et al., 2006), and 25 km of fungal hyphae (Hinsinger et al., 2009). Soil animals may constitute more than 20 percent of the total diversity of living organisms presently described (Lavelle et al., 2006) and represent 50 percent of the total animal biomass on Earth (Fierer et al., 2009). Despite this abundance, soil biota are extremely heterogeneous and patchy in occurrence, and for many biota the soil is a nutrient and moisture desert occasionally swept by storms of infiltrating water. These biota make their own world.

Ecologists are exploring what causes such diversity, what distinguishes functional groups and their relationship to environments, and how to map and explain the diversity in the few grams of soil to that found in entire landscapes. In the shallow region of the soil, the two biotic worlds are linked: plant production feeds soil organisms, while decomposition of plant waste in the soil by these organisms provides nutrients to plants. This linkage is much richer, however, than just production and decomposition (Figure 3-4) and has led to considerable research on the above- and belowground interactions. Soil organisms also may be differentiated by the presence of water: fungi, some nematodes, and arthropods live in air-filled pores, whereas bacteria, protozoa, and other nematodes live in water-filled pore spaces and water films.

The connection of water and life is perhaps most strongly expressed in the rhizosphere (i.e., the volume of soil surrounding a living root). In this small volume, plant life, and all that depends on plants, is sustained. The biogeochemistry, biophysics, and ecological processes in the rhizosphere are still relatively poorly known, but it is clear that water content and distribution play a central role. Just the simple selection process in which some plants can grow and maintain roots in drying soil while others cannot may determine vegetation community composition (as well as agricultural practices). Plants not only extract moisture but also, via hydraulic lift in which water from deeper roots is brought up and discharged out of roots into shallow soils, may add moisture (during nighttime favorable potential

SOILS—THE FINAL FRONTIER

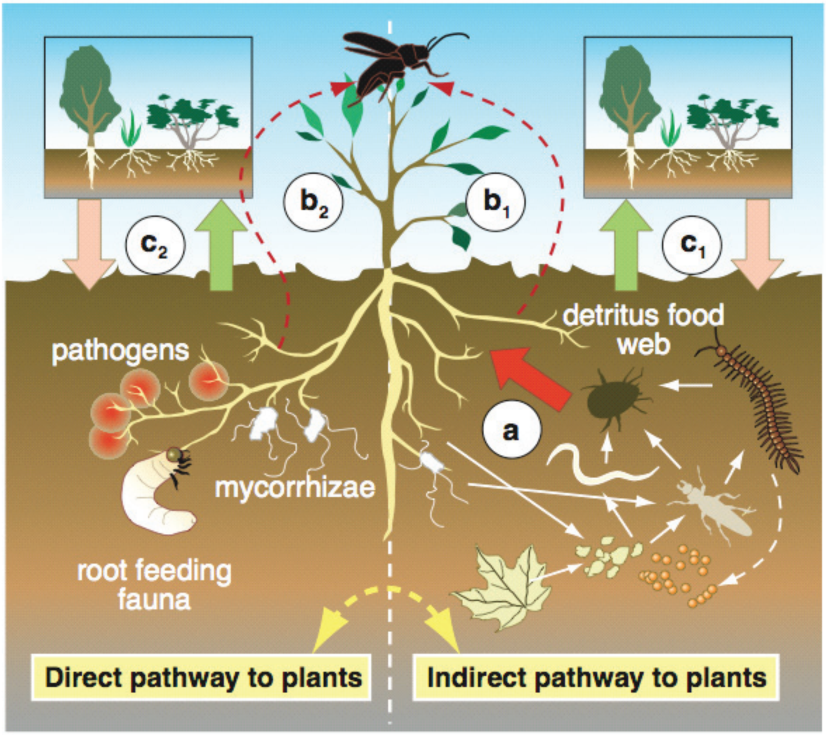


FIGURE 3-4 An illustration of the linkages between aboveground communities and communities in the shallow region of the soil. From Wardle et al. (2004): "(Right) Feeding activities in the detritus food web (slender white arrows) stimulate nutrient turnover (thick red arrow), plant nutrient acquisition (a), and plant performance and thereby indirectly influence aboveground herbivores (red broken arrow) (b_1). (Left) Soil biota exert direct effects on plants by feeding on roots and forming antagonistic or mutualistic relationships with their host plants. Such direct interactions with plants influence not just the performance of the host plants themselves, but also that of the herbivores (b_2) and potentially their predators. Further, the soil food web can control the successional development of plant communities both directly (c_2) and indirectly (c_1), and these plant community changes can in turn influence soil biota." SOURCE: Reprinted, with permission, from Wardle et al. (2004). © 2004 by The American Association for the Advancement of Science.

gradients). This effect has been shown to have consequences not just for moisture availability to plants. The hydraulic conductivity of soils depends strongly on soil moisture; therefore fluxes of water into and out of the soil can be affected by hydraulic lift. In addition, because transpiration exports the lifted water to the atmosphere, there may be a significant influence on regional humidity, temperature, and thus climate even on the scale of the Amazon basin. Hydrologic processes connect relatively deep groundwater, as well as the rhizosphere, to the atmosphere.

Soil developed on sediment deposited by rivers (most obviously on Earth's the great lowland floodplains) causes material properties to change significantly from the original source material. But this change is not surprising compared to the drastic alteration that occurs in the transformation of bedrock to soil. Bedrock, strong enough to be cut into slabs and used in buildings, can, over time, be reduced to an assemblage of loose soil particles bearing no physical resemblance and limited chemical similarity to the parent material. Often this soil is essentially the digested residue of life. In many environments it is the persistent burrowing, chewing, and dissolving by biota that destroy the rock structure and produce a loosened soil. Soil biota transform dense rock into a permeable, moisture holding, chemically diverse environment, through which infiltrating waters pass and chemically evolve. Earthworms are especially important, and the invasion of exotic earthworms in North America has changed nutrient dynamics and soil structure, leading to changes in plant community composition (i.e., Boyer and Wratten, 2010). Elsewhere, ant and termite colonies can be especially important in creating patchy disturbance. Bioturbated soil in general is extremely heterogeneous, with areas of tightly held water that may remain well beyond a rainy season, and pathways of rapid preferential flow established by soil fauna and roots. Such differential retention would contribute to the age distribution function of water entering channels. Roots can also be pathways for rapid injection of incoming soil water to considerable depth (hydraulic redistribution). To model watershed dynamics, hydrologic scientists often use "pedotransfer functions."[2] Biota's influence on soil characteristics is not captured solely by the soil texture they helped create. How can the effects of soil biota on the hydraulic properties of soils be quantified?

Hydrologists have a central role in developing an understanding of Earth's carbon cycle, and for soils, which are estimated to contain 80 percent of the planet's terrestrial carbon, this is especially true (Nielsen et al., 2011). Models are exploring and field experiments are examining vegetation

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[2] A pedotransfer function is a relationship that allows estimation of soil hydraulic properties (water retention and hydraulic conductivity) from soil characteristics such as texture (sand, silt, and clay content).

responses to anticipated increased CO_2, which may include CO_2-induced stomata closure, increased moisture content, and increased leaf area index. Soil organisms play a primary role in organic matter decomposition, but temperature and moisture content mediate soil biota and may be affected either directly by changes in climate or indirectly by CO_2-mediated changes in plant water use efficiency and evapotranspiration. The interdependence among CO_2, soil moisture, plant growth, and transpiration may have contributed to controlling the range of CO_2 over geologic time scales. Coupled soil moisture, soil biota, and vegetation assemblage studies are needed to explore the role of belowground organisms in influencing theses outcomes.

Subsurface ecosystems and the interdependence between vegetation and belowground biota are a frontier area of research in which water abundance, seasonality, and spatial distribution play a first-order role. Should models directed at the coupled evolution of vegetation assemblages, topography, and local climate account for the equally evolving soil biota and their influence on hydrologic and biogeochemical properties? How do organisms in soil and weathered bedrock influence solute chemistry of runoff? Can the effects of soil organisms on hydraulic properties and the resulting age distribution of water and preferential pathways be predicted?

3.4. Critical Links in Aquatic Ecosystems

Hydrologic flow regimes, river channel dynamics, and aquatic ecosystems are linked, resulting in a co-evolution of rivers and river ecosystems.

The statement “rivers are the authors of their own geometry” (Leopold and Langbein, 1962) captures the central idea that, simply through the interaction of water flow and sediment transport, natural rivers create highly regular, self-contained channels. Rivers, for example, can migrate across their floodplains, leaving meander cutoff loops, and do so for thousands of years and yet show no significant change in average channel width. Internal scaling within river systems is so strongly developed that it is not possible without a scale bar to tell the size of a river from a map of channel platform. This dynamic regularity (rivers are rarely fixed in place) creates repeated, heterogeneous environments to which aquatic ecosystems are finely tuned.

Efforts to reproduce this regularity in laboratory channels have met with great success when flume walls are fixed and water discharge and sediment supply are held constant. Laboratory experiments with erodible banks, however, have had little success, and only recently have lateral migrating channels with cutoffs been created experimentally. For such channels to develop, some bank strength beyond that created by frictional resistance of sand and gravel is needed. One important source of strength is vegetation. Hence, riparian vegetation is not simply following river courses; rather it is strongly influencing the course, form, width, and dynamics of rivers. Vegetation invades exposed bars during seasonally low flow and stabilizes them against subsequent change. Fallen trees create local complex environments where they partially block river flow, and prior to land use management, large jams of fallen trees would form and redirect even fairly large rivers. Similarly beavers (genus *Castor*) in North America and Europe once converted smaller streams into chains of lakes, and modified the form and path of larger ones. River morphodynamics and river ecosystems are interacting and interdependent. The relative strength and importance of these interactions depend on flow and sediment regimes and river size. Considerable theoretical progress has been made in the prediction of channel flow, sediment transport, and bed morphology for fixed channel width in the absence of strong biotic influences. Needed are field observations and theory that explicitly link river morphodynamics with aquatic and/or riparian ecosystems. Research has begun, driven by not only the search for answers to the fundamental questions, but also the goal of guiding river restoration and redesign.

Human-induced changes in flow regimes alter not only the spatial extent and quality of freshwater habitats but also the connectivity between freshwater ecosystems. As habitat quality and quantity decline and freshwater systems increasingly fragment, aquatic and floodplain species are being lost and the water quality of the world's rivers and coastal zones is being degraded. A central challenge for the hydrologic and ecological community is to find common ground in understanding the complex ways that flow regimes impact critical geomorphic and ecological processes and in turn the maintenance and dispersal of organisms in aquatic ecosystems.

What are the critical components of river hydrologic regimes that dictate composition and dynamics of aquatic ecosystems?

The great physical diversity of river and floodplain habitats is critical to the evolution and maintenance of freshwater biodiversity. The form, dynamics, and resulting interactive ecosystems of river channels are driven by flow characteristics, sediment load (and size), bank resistance, confinement, and channel slope. The morphodynamics of rivers systematically changes downstream as they drain larger watersheds, carry more water and sediment, and become less steep. Rivers create a network of numerous small channels feeding larger ones that generate repeated habitats across the landscapes and different but linked habitats (e.g., where small channels enter large ones). Coarse-bedded steep upland rivers are confined in canyons and experience localized shifts where tributaries enter. As valleys widen downstream, rivers will sweep and shift laterally and flood periodically, creating seasonal habitats that may be vastly more productive than in-channel environments. Biota influence channel morphology through controlling bank strength (e.g., rooted vegetation), trapping fine sediment, and redirecting flow and sediment (e.g., through fallen wood and beaver dams). Hence, there is a co-evolution of rivers and river ecosystems. This co-evolution can be disrupted either by changes in external drivers (e.g., climate and tectonics) or by changes in internal interactions (e.g., sediment pulses, vegetation dynamics, or the introduction of non-native species, Figure 3-5).

In addition to its role in shaping a river system's physical habitat, the flow regime is itself an important determinant of the distribution, abundance, and life history traits of river and floodplain (riverine) organisms within its basin. Flow magnitude, frequency, timing, duration, rate of change, and predictability of flow events (e.g., floods and droughts) act

FIGURE 3-5 The introduction of the beaver *Castor canadensis* to Tierra del Fuego, an archipelago off the southernmost tip of South America, created extensive damming of streams and converted nearly 30-40 percent of the island's riparian *Nothofagus* (or southern beech) forests to floodplain wetlands (Anderson et al., 2009). SOURCE: Photo courtesy of Christopher B. Anderson, University of North Texas.

both individually and collectively as constraints on population growth or determinants of successful life history traits. Many aquatic organisms synchronize their life-cycle events to the occurrence of flow regime events. For example, many aquatic insects time their emergence to avoid annual bottlenecks of peak flows or droughts, and many fish time their migrations through river networks to minimize the risk of being stranded in disconnected habitats. Many fish depend on the seasonal inundation of floodplains of lowland rivers for food and reproduction, in tropical (Junk, 1984) and temperate (Gorski et al., 2010) river systems. A wide variety of terrestrial organisms may tune their distribution and behavior to these river patterns, with organisms as diverse as humans, bears, bats, lizards, spiders, and riparian plants relying on peaks in insect emergence or fish spawning to supply a substantial portion of their annual energy or nutrient demands.

Flow regimes are being affected by land use disturbance (especially dams, water withdrawal, and channelization) and climate change. As flow regimes change, the winning evolutionary strategies of the past may prove less competitive so that native species may be lost and new species may become dominant or invade aquatic ecosystems from which they were previously excluded. Although it is clear that water resource management that is more sophisticated than merely protecting minimum flows is necessary, a central challenge for understanding the modern distribution of riverine organisms (and the terrestrial organisms that rely upon them) is to determine which aspects of the hydrograph are most closely associated with the protection, maintenance, and restoration of biological communities and ecosystem processes.

Many questions remain. How do river food web networks depend on river networks? What components of a river's hydrologic regime are essential to channel morphodynamics and river ecosystems? What is a necessary amount of sediment supply (and size of sediment) to maintain or rebuild river ecosystems? How will changes in flood frequency regimes or extended periods of drought flow (associated with climate change or land use) alter channel (and floodplain) habitat?

3.5. Hydroecosystems in Transition

Earth's ecosystems are in a state of transition as a result of climate change and changing land use.

The term ecosystem refers to "any area of nature that includes living organisms and nonliving substances interacting to produce an exchange of materials between the living and nonliving parts" (Odum, 1959). An ecosystem generally encompasses a region of relatively homogeneous biological composition and is distinguished from other regions by markedly different composition. For example, scientists would recognize a forest ecosystem as separate and different from a grassland ecosystem. Of course, where forest meets grassland, there is a transition zone, often called an ecotone. Organisms are conditioned to a certain range of conditions in the physical environment, and changes in the physical environment can lead to transitions in ecosystems. If air temperatures rise in the Arctic, for example, the tree line may move poleward and potentially displace tundra ecosystems completely. Ecosystem transitions are known to have profoundly impacted humans in the past and can be expected to be impactful in future. The processes that determine transitions in ecosystems are not well characterized or understood. Two examples of hydroecosystems in transition and related research are discussed below.

How will the sensitive extremes of Earth's hydroecosystem, that is, the cold regions and warm deserts, respond to climate change and land use change?

Climate change has sparked a great expansion of research in cold regions (including the polar regions and high mountains) to document, explain, and predict changes that inevitably will come. In part because of recent major reports, for example, the Arctic Climate Impact Assessment (ACIA, 2005) and the Intergovernmental Panel on Climate Change (IPCC, 2007), observations and concerns about these cold-region systems have gained wide attention. Much has been written about glacier retreat and instability. Although glaciated landscapes are important, a large region on Earth is not currently covered with glaciers but experiences cold climate. Changes to this region caused by climate change will feed back to climate evolution itself. These regions include the 80 percent of Alaska and 22 percent of the Northern Hemisphere that is affected by frozen ground (permafrost).

Some expected changes have already been detected, while others have not. A complex weave of positive and negative feedbacks, but mostly positive (self-reinforcing), arise from many sources, including snow depth change, streamflow variation, stability of permafrost, forest expansion into tundra, deciduous tree expansion, albedo reduction, carbon and methane release, fires, increased transpiration, and changes in surrounding sea-ice cover. Research should delve into this complexity to enhance the ability to predict the rate, magnitude, and nature of change and sort out the sign and intensity of various feedbacks. Changes in the depth and patchiness of permafrost can change terrestrial water storage and flow paths, thus influencing biogeochemical processes and vegetation features such as albedo, and susceptibility to insect destruction and fire. Hence, understanding changes in hydrologic processes is central to understanding how vegetation and climate may co-evolve.

Thawing of the permafrost also may profoundly affect erosional processes. Landslide may become more frequent and widespread where liquid water forces elevated pore pressures. Melting water may lead to gully formation and potentially widespread increase in sediment production. Ice strengthens river banks and may play a central role in controlling channel morphodynamics; permafrost melting will change the rate of river shifting in meanders and the perseverance of meandering over braided forms. Similarly, melting permafrost may increase coastal zone erosion, releasing sediment and organic matter. These geomorphic transitions may in turn influence greenhouse-gas release, nutrient supply to food webs, river navigation, and infrastructure (e.g., pipelines, roads, and housing). For example, a significant amount of the world's carbon is stored in frozen Arctic soil (Oechel et al., 1993). If rising temperatures cause the permafrost to melt and the organic matter contained therein to be broken down by bacteria, huge amounts of greenhouse gases will be released (Schiermeier, 2001).

Global climate models forecast expansion of Earth's warm desert regions, but the rate of change will depend on various feedbacks associated with shifting vegetation that alter albedo, evapotranspiration, and surface roughness. Studies have focused on how decreased water availability and elevated temperature will change the composition and structure of vegetation communities (including the invasion of exotic plant species), which will in turn affect the entire ecosystem and the regional climate. Other effects, including vegetation response to increased CO_2, nitrogen deposition due to pollution, and changes in fire frequency (mediated in part by grazing), add uncertainty about the pace and magnitude of landscape change. Reduced vegetation cover will increase dust, which will have direct effects on climate and hydrologic processes (dust deposition on alpine glaciers leads to accelerated melting). Model results also point to reduction in streamflow and loss of critical water supplies to both humans and ecosystems. Predictions about the future of deserts will depend on new research that explores and explains these ecological, hydrologic, and climatic interactions. How will land cover change and water extraction exacerbate or alleviate desertification trends? How will physical and biological responses to desertification in turn alter local and regional climate?

What controls the low flow extent of stream networks?

Low flow in rivers can be defined by the extent of continuous (perennial) flow and by the magnitude of that flow (relative to channel size). River organisms at low flow are confined to narrow strips of water emanating from upland sources. The uppermost tip of the permanent stream network defines the reach of perennial flow and is, therefore, a major ecological boundary. The extent of the stream network also strongly influences stream temperature. Upstream of the perennial flow, seasonally isolated pools may form, or the stream may become completely dry (periods of zero flow). Of course, the smaller the drainage area, the more likely this critical transition will be crossed, but relatively large channels can also go dry where flows are insufficient. This regularly happens in arid landscapes and during extreme dry periods in more humid landscapes, but also where water diversions, sometimes by streamside groundwater pumping, reduce surface flow.

The perennial streams that show up as "blue lines" on official U.S. Geological Survey maps are typically based on inference rather than direct observation of flowing water. Some empirical studies have used multivariate analyses between physical features (drainage area, slope, and so on) and observed perennial, ephemeral, and intermittent streams to estimate the perennial flow channels, but such approaches have no ability to anticipate how the extent of such channels may change under varying land use and climate. Climate change will change the nature of river flows in the world (e.g., Milly et al., 2005). The consequences for aquatic ecosystems have received little study and essentially no systematic observations of or theory exist to predict the full spatial extent of perennial flow in river networks.

An increased emphasis on these critical hydrologic bottlenecks for aquatic organisms—low and zero flow periods—is needed in order to protect the biodiversity of aquatic ecosystems. Periods of low flow are integral parts of the hydrograph for many rivers and are necessary for many processes in riverine ecosystem functioning. A number of important ecological processes center around low and zero flow periods. Yet during low flow periods habitat availability contracts and suitable freshwater habitats become fragmented, which can have negative implications for the dispersal of organisms and materials through river networks. Competition for resources is intensified, and predation risk increases when habitat and other resources become limited at low flows. Habitat quality often declines in contracting aquatic habitats (e.g., rising salinity, decreasing dissolved oxygen concentrations in contracting isolated pools of a dryland river). Under extreme drought, freshwater organisms are restricted to rare refugia, where poor water quality and intense competition may drive some species to local, regional, or global extinction.

Besides mapping the spatial extent of perennial flow through channel networks it is also important to quantify low flow discharges. (Of course, quantifying low flow hydrology is important to humans as well as to ecosystems, see Box 3-2.) In order to understand and predict ecological responses to altered flow regimes it is critical to be able to both measure and model low and zero flow hydrology. Low flow hydrology has received relatively little attention from researchers (Smakhtin, 2001) in comparison with stormflow generation. The mechanisms of flow generation at low flows in catchments should be better understood so the impacts of land use and climate changes on aquatic organisms can be assessed. Given the need for low flow measurement and modeling to understand critical ecological responses to flow management, there is a compelling case for hydrologic scientists to work with ecologists to solve these hydroecological problems to provide the tools needed to make better ecological predictions.

What sets the spatial extent of streamflow in a given channel network, and how does this extent (and flow magnitude) vary seasonally? How will the flow network change in droughts? What will be the effect of predicted climate change on the low flow stream network? How will aquatic and riparian ecosystems respond to low flow channel network contraction and to reduced perennial flow? Are small systems more sensitive to stress from climate variability and water extraction because of an increased likelihood of crossing critical thresholds (e.g., cease to flow)?

3.6. Conservation and Restoration Hydroecology

Theory and mechanistic field studies are needed to guide the protection, redesign, and restoration of ecohydrologic functions on landscapes.

A fundamental shift has taken place in how society values natural processes and manages landscapes. Wetlands, once considered low-quality land in need of drainage, are now known to provide a wide range of critical ecosystem services, from flood control to essential habitat for commercially important species. Rivers, viewed largely as large-scale canals, were blocked from migration, cut off from their floodplains, and depleted of sediment and water. Now efforts are under way to restore natural processes to rivers and wetlands in order to regain aquatic ecosystems' functions and flood management. Vegetation management, whether through fire control, grazing practices, agriculture, or industrial timber production, is now seen as having a dual objective of resource use and maintaining or regenerating desired ecosystem outcomes. Goals are being stated that, for example, would lead to sustainable timber production and functional ecosystems. Is it possible that better practices will benefit both resource exploitation and ecosystem function? Can natural systems and the ecosystem services they provide be made resilient to anticipated environmental change?

To answer these questions, knowledge of the coupled hydrologic processes, geomorphology, and ecology of these systems is essential. Management actions for a desired outcome, whether changing grazing practices or adding wood to streams, are based on predictions (by inference, experience,

BOX 3-2
Drought and Urban Water Supply

The recent 2-year drought in the southeastern United States (2006-2008) was dubbed one of "historic proportions," because major metropolitan areas as well as surrounding rural communities from North Carolina to Alabama faced an emergency so serious it gained national attention (Figure 3-6). At one point, Lake Lanier, Atlanta's main water supply, contained only 90 days of water supply. The severity of the situation fanned the flames of the debate surrounding the allocation of water from two large river systems in the southern states of Alabama, Florida, and Georgia—the Apalachicola, Chattahoochee, and Flint rivers, and the Alabama, Coosa, and Tallapoosa rivers (NRC, 2009). A centerpiece of this debate is how much water should flow from Georgia's Lake Lanier, a reservoir critical to Atlanta's water supply, to Florida's Apalachicola Bay a supply that is critical to the Florida Panhandle's oyster and fishing economy. The supply of reservoir water is also critical to ecosystems along the way to the Florida Panhandle—ecosystems that include protected species like the fat three ridge mussel and Gulf sturgeon, as well as many other species. A recent study (Seager et al., 2009) shows that this drought was climatically less severe than even the Southeastern drought that occurred in 1998-2002. When extended records of hydroclimatic variability from tree-ring data were considered, the 2006-2008 drought was found to be much shorter than numerous past droughts (Figure 3-7).

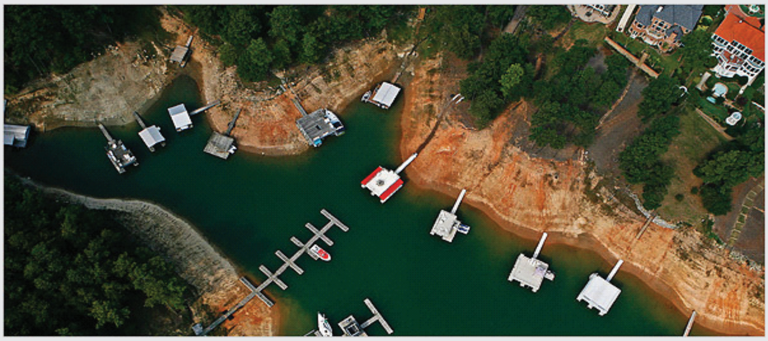

FIGURE 3-6 “CUMMING, Georgia—With water supplies rapidly shrinking during a drought of historic proportions, Governor Sonny Perdue declared a state of emergency Saturday for the northern third of the state of Georgia and asked President [George W.] Bush to declare it a major disaster area. Georgia officials warn that Lake Lanier, a 38,000-acre reservoir that supplies more than 3 million residents with water, is less than three months from depletion. Smaller reservoirs are dropping even lower.” SOURCE: Quote available at http://www.msnbc.msn.com/id/21393296/ ns/weather/t/georgias-governor-declares-drought-emergency/; image: Lake Lanier Reservoir, Fall 2007. Reprinted, with permission, from Pouya Dianat, *The Atlanta Journal-Constitution*. Available at http://www.nytimes.com/2007/ 10/16/us/16drought.html.

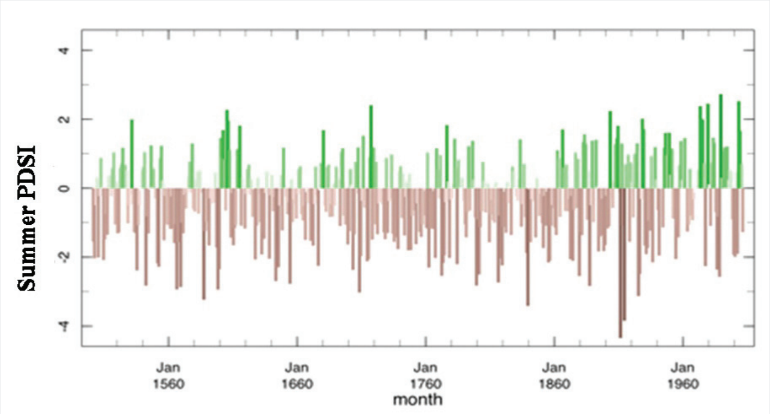

FIGURE 3-7 Summer Palmer Drought Severity Index (Summer PDSI) averaged over the Southeast United States reconstructed from tree-ring data for the period 1000-2006 A.D. PDSI is based on a water balance estimate. The larger the negative number, the more severe the moisture deficit and the stronger the drought. Note the frequent occurrence of multi-decadal drought conditions. SOURCE: Reprinted, with permission, from Seager et al. (2009). © 2009 by American Meteorological Society.

or more quantitative approaches). Currently lacking are both sufficient understanding from field studies and quantitative models to make reliable predictions about desired outcomes from management decisions in many applications.

What will make wetlands restoration work?

As an environment that transitions between land and water, wetlands are the ultimate theater for the interaction of biota and hydrologic processes. Although vaguely defined in common language, wetlands are nonetheless now commonly understood to be vital parts of Earth's surface, playing a unique role in regulating biogeochemical cycles and providing much more than habitat for birds, fish, and other organisms. Terms such as peatlands, marsh (no trees), swamp (trees present), bog, fen, playa, vernal pool, and meadow are used to distinguish wetlands. These distinctions highlight different coupled hydrologic and ecologic systems that have emerged across the planet. But three components of these systems are often used to define them as wetlands: (1) the seasonal or permanent presence of shallow standing water or groundwater saturation, (2) soils that show the effects of seasonal or permanent saturation, and (3) vegetation adapted for this condition (which involves seasonal or permanent low oxygen levels at root level). These three attributes, in fact, are formally used in U.S. regulations to define the presence of wetlands and the necessary management of them. One common element exists: wetland ecosystems are strongly dependent on subtle changes in the duration, frequency, and magnitude of water at or above the ground surface.

Once systematically drained to prevent disease and facilitate agriculture, wetlands in the United States are now legally protected and formally recognized for the variety of "ecosystem services," they provide which include the following:

(1) key habitat for many organisms including harvested biota;[3]
(2) flood mitigation by storing river floodwaters;
(3) coastal storm surge abatement through wave attenuation and flood storage;
(4) aquifer recharge;
(5) water quality improvement by retaining contaminants such as excess nutrients;
(6) timber production;

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[3] The majority of fish and shellfish species harvested commercially in the United States are wetland-dependent in some phase of their life cycle, and perhaps two-thirds of the fish harvest depends on coastal and inland wetlands (Mitsch and Gosselink, 2000).

(7) habitat for endangered and threatened species (particularly waterfowl and fish);

(8) agriculture (e.g., native rice production, water supply, and nutrients);

(9) carbon sequestration (globally wetlands occupy approximately 6 percent of the land surface but are estimated to store more than half of global soil carbon (Reddy and DeLaune, 2008)); and

(10) energy resources (peat harvested and burned).

Many of these benefits have become apparent in the United States in recent years, whether it is through the effects of wetlands loss or the effects of Hurricane Katrina in 2005 along the Gulf Coast or the value of floodplain storage during flood events that sweep down the Mississippi River (Box 3-3). Yet, despite these values perhaps one-half of the world's wetlands are gone, and the loss of wetlands continues. In some areas, the loss is greater, including California, where it is estimated that only 10 percent of the original wetlands remain. In the United States more than 70 percent of the remaining wetlands are on private lands (Copeland, 2010); consequently, defining wetlands and valuing their ecosystem services take on elevated significance. The concern is global, as expressed by the Ramsar Convention of 1971,[4] which is the only global environmental treaty that deals with a specific ecosystem.

Wetlands are being constructed, redesigned, restored, and protected, and each of these actions calls for increased scientific understanding of wetland functions and the interconnected hydrologic, biogeochemical, and ecological processes. In response to this need, research on wetlands has exploded in the past 20 years (Zhang et al., 2010). The practice of making "constructed wetlands" has become a particularly important management technique aimed at removing contaminants from contaminated waters. Constructed wetlands are now used in agriculture, urban runoff, mining, sewage treatment, and other industrial and municipal waste treatments needs. Theory has guided construction of these wetlands, but models have tended to be a "black box" where the detailed mechanisms driving biogeochemical processes are not explicitly treated.

The challenge of wetlands protection raises many basic research questions. What flow duration and timing is necessary to protect extant wetlands? How can we manage the hydrologic regimes of natural, restored, and constructed wetlands to most effectively retain and remove contaminants or to protect species dependent upon wetland ecosystems for all or part of their lives? How do vegetation development and subtle flow dynamics lead to distinct self-organized patterns of vegetation assemblages? How will

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[4] See http://www.ramsar.org.

BOX 3-3
Mississippi Delta Restoration

The Mississippi River Delta has lost about one-third of its original wetland since European settlement of North America. This wetland provides many ecosystem services, most notably freshwater habitat and storm surge protection. At the current rate of land loss and shoreline migration, it is estimated that New Orleans will be exposed to the open sea by 2090 (Fischetti, 2001).

The reduction of sediment supply to the delta due to dam construction in the Mississippi watershed has contributed to this land loss. But presently the main cause of land loss is the confinement of the river to levees, which have created an efficient "pipeline" of sediment (and nutrients) directly out to the Gulf of Mexico. The levees prevent the river spilling into adjacent coastal basins, where sediment deposition would provide the mineral base for wetlands vegetation growth and thus sustain the delta level. Without this resupply the coastal wetlands drown because of natural and anthropogenic (due to hydrocarbon extraction) subsidence and sea-level rise. The final result is open water with no remaining wetlands ecosystem services.

Engineered avulsions, in which river flood flow is directed into coastal basins, had been proposed, but doubts were raised about sufficient sediment supply, the high rates of subsidence, and the anticipated effects of climate change induced sea-level rise. Figure 3-8 shows an example, however, where numerical modeling performed as part of the delta dynamics integrated research project of the National Center for Earth Surface Dynamics demonstrates the possibility of land building. This model suggests that effective land building can be done without threatening navigation or demanding a large fraction of the Mississippi flood flow.

Basic research is needed to guide such a major restoration project. Recently NSF funded a "Delta Dynamics Collaboratory" that will support an intensive field observatory (the Wax Lake Delta, a recent, actively growing delta about 100 km west of the main Mississippi delta) and a modeling activities center associated with the NSF supported Community Surface Dynamics Modeling System (CSDMS) at the University of Colorado. The interaction of sediment supply and wetland ecosystems dynamics will be a primary focus.

hydrologic change (climate induced or managed) prevent or exacerbate the spread of invasive species in wetlands? How will the critically important role of wetlands in global carbon cycling change as a result of climate change or direct hydrologic alteration?

Although many restoration efforts are under way, there is considerable controversy about their effectiveness. It is argued that constructed wetlands are not a substitute for naturally formed ones, because they fail to perform

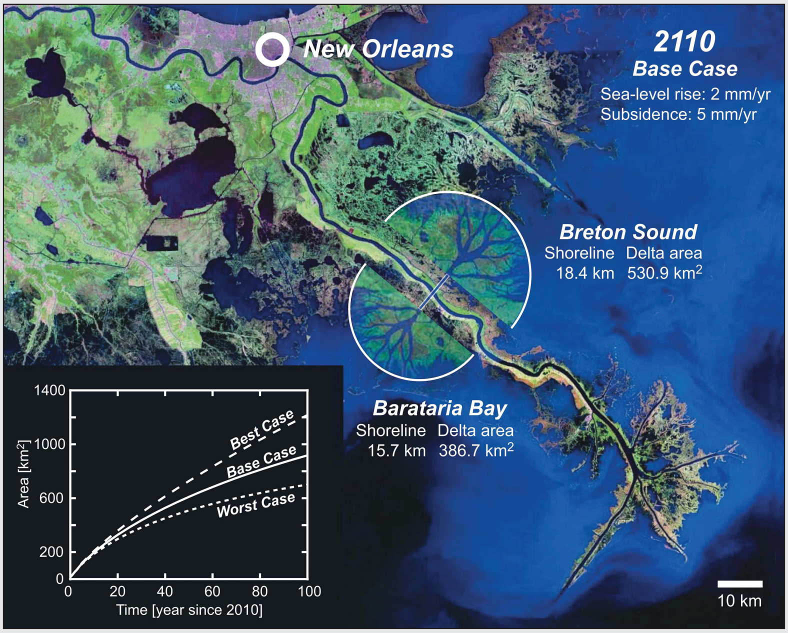

FIGURE 3-8 View of the delta of the lower Mississippi River below New Orleans, showing predictions of the new land (delta surface) that could be built over 100 years starting from 2010. Two diversions are considered: Barataria Bay and Breton Sound. The calculation is based on a "base case" scenario: a subsidence rate of 5 mm per year and sea-level rise rate of 2 mm per year. The inset shows results for a "best case," subsidence rate of 1 mm per year and sea level rise rate of zero mm per year, and a "worst case," with corresponding values of 10 and 4 mm per year. For the sake of clarity, land losses in the part of the deltaic wetlands not subject to diversion are not estimated or shown. SOURCE: Reprinted, with permission, from Kim et al. (2009). © 2009 by the American Geophysical Union.

the same hydrological, ecological, and biogeochemical functions. Monitoring the effectiveness of restoration (and redesign) of wetlands is typically not included in projects, so the opportunity to learn and make adaptive management decisions is limited. Redesign may be the more common option for large wetlands. In this case, the original wetlands system cannot be reconstituted because of permanent changes in land use and hydrologic routing (e.g., through dams, diversions, and drains). California's San Francisco Bay Delta Estuary, the Florida Everglades, and the lower Mississippi River wetland systems are prime examples of systems with strong constraints, multiple goals, and a complex community of users. Although exceptionally to produce challenging, coupled models of hydrological, ecological, geochemical, and geomorphological processes are needed to enable communities to make reasonable comparisons about the costs and benefits of alternative management decisions.

Wetlands research presents a great opportunity to explore and discover the subtle linkages among water level (flow, duration, and frequency), vegetation establishment and growth, soil chemical evolution, aquatic vertebrate and invertebrate dynamics, and morphologic evolution of subdued and emergence landforms. Wetlands produce distinct landforms, vegetation patterns, and ecological interactions that invite model development—and much work has been done to explore essential controls on wetlands attributes. Nonetheless, wetlands, especially large lowland systems, remain challenging to study because of their size, access difficulties, and the dispersed nature of ecologic and hydrologic processes (Harvey et al., 2009). Remote sensing data (including current and future satellites for mapping water level and storage) and high-resolution topographic data (of ground and water surfaces), coupled with process oriented field studies, can reveal underlying mechanisms and processes. What are the key controls on large wetland system function and services? What are the minimum features required to build mechanistic models linking ecosystem, biogeochemical, and hydrologic processes that will increase the efficacy of wetlands restoration? Can wetlands be constructed, restored, or redesigned to provide resilience to the consequences of global change?

What will make river restoration work?

In the United States and throughout the world, restoration of rivers and streams is an increasingly common approach to managing freshwaters. This trend reflects a growing awareness of river degradation and societal desires for waterways that provide beneficial human uses while sustaining biodiversity and ecosystem goods and services. Rivers drain landscapes and thus their form and dynamics are linked to the cumulative land use activities across their watersheds. Land use alters the water runoff rate and stream temperature, sediment supply (size and amount), and water chemistry that a river receives and passes downstream. Rivers are straightened, dredged, leveed (preventing access to adjacent floodplains), confined in hardened banks, stripped of in-channel woody debris and riparian vegetation, diverted, and covered. The combined effects of altered flow, sediment, and nutrients regimes together with altered physical states have led to significant degradation of river biodiversity and to significant increases in the delivery of pollutants to estuarine and off shore environments. Non-point-source contamination, channel degradation, and aquatic species loss or decline are among the most common motivations for undertaking stream restoration (Bernhardt et al., 2007). River restoration projects typically attempt to reestablish the water and habitat quality of degraded streams using one of two overarching approaches, either focusing on reestablishing hydrographs and hydrologic connectivity (hydrologic restoration) or focusing on restoring habitat form (hydromorphological restoration).

Hydrologic restoration includes "reestablishing part of the historic flow regime, removing levees to recover floodplain functionality, scheduling water releases from reservoirs to restore native vegetation and riparian functions, and in some cases even removing flow blockages or reconnecting river reaches that have been fragmented" (Bernhardt and Palmer, 2011). Dam removal, in particular, has become a widespread practice, often resulting from relicensing assessments. A central goal of hydrologic restoration is to reestablish natural processes such that the river system will create flow and morphologic dynamics critical to maintaining ecosystems. Hydromorphological restoration places greater emphasis on increasing channel stability and in-stream habitat by altering channel form and structure along a river reach in order to restore biodiversity and ecological function. Commonly this approach employs introduction of in-channel structures (using boulders or large woody debris). Whole reaches of channels may be redesigned to a fixed channel pattern to meet some desired form and assumed function. But restoration projects have also been designed with the goal of channels recovering their morphologic dynamics, such as shifting laterally and thereby creating increased habitat complexity. Reports monitoring the effectiveness (pre- and post-restoration quantitative sampling) of restoration outcomes are rare (Bernhardt et al., 2005), but some hydrologic restoration efforts have been success stories (e.g., Hall et al., 2010). In contrast, there is limited evidence of demonstrable ecological improvements resulting from hydromorphological restoration projects (Bernhardt and Palmer, 2011), despite the fact that these types of projects are extremely common worldwide.

Restoration projects are mostly implemented without detailed understanding of the watershed context and potential channel morphodynamics. Typically, limited, if any, ecological field studies precede project implementation. This is especially true in hydromorphological studies, which commonly rely on the assumption that adding structures to channels or redesigning a channel to a particular form will create an ecological benefit. Restoration projects commonly lack two critical components: (1) an ecological assessment to determine limiting factors to species success in order to define what restoration would be most effective and (2) analysis of sediment supply and consequences for restoration strategy (e.g., Rosenfeld et al., 2010).

Forty-five percent of the nation's assessed rivers are classified as endangered or impaired (EPA, 2000); thus, considerable work is still ahead. The restoration measures taken will vary greatly and depend on the ecosystem, the river and its watershed, and practical constraints. There is a need for development of quantitative models that explicitly link hydrologic, geomorphic, geochemical, and ecologic processes and that enable users to ask "what if" questions regarding restoration measures in a changing environment. The large number of river restoration projects offers many opportunities for testing basic hydrological, biogeochemical, and ecological understanding. If river sediments and their contaminants are responsible for downstream ecosystem decline, can restoration measures increase upstream retention? In a watershed where a large portion of its network of rivers is degraded and water quality is poor, what are the most effective procedures to restore habitats and aquatic biodiversity? How can key barriers (physical, chemical, or temperature) to stream biota migration be efficiently identified and eliminated? What is necessary to restore or redesign a channel such that it becomes a self-maintaining, morphologically dynamic river that passes water and sediment and supports a diverse ecosystem? Can scientists predict fish population dynamics for various restoration measures and anticipated effects of changing climate and land use? Such questions will naturally be best answered by interdisciplinary teams of scientists and engineers; and high-quality hydrologic research should be at the center of these inquiries.

CONCLUDING REMARKS

In the past 20 years a major shift has occurred in the hydrologic community to embrace and explore all the ways water and life interact on Earth. Hydrologists are investigating how interactions that link subsurface, terrestrial, and freshwater environments are controlled by and contribute to ecosystem dynamics and the planet's evolving climate. Theory is rapidly developing, with mathematical models and process-rich numerical schemes being proposed. Opportunities for basic discovery occur at all scales, from the micrometer-scale processes surrounding root hairs to the regional and global scale of water exchange with the atmosphere. These opportunities require deep understanding of not only physics, chemistry, and biology of processes, but also natural history and modeling.

If there is one common goal, then it is to gain enough understanding of these interactions, so that models, whether conceptual, analytical, or numerical, can provide reliable predictions of the future states of the Earth system. The more scientists are able to anticipate future states, the better society will be able to prepare for them or alter what might otherwise occur. Models are needed to predict consequences of local changes (e.g., vegetation conversion for energy crops) as well as global changes (e.g., increasing CO_2 in the atmosphere). It is vital that biotic processes be made explicit in such models. This advance, however, will reveal the uncertain future. Ecosystems are dynamic, time dependent, nonlinear, and complex. Biotic interactions, disease, behavior, and other attributes far different from purely physical or chemical processes challenge the goal of predictability. The pursuit of answers to the kinds of questions raised in this report, which explicitly seek to include life-water interactions, should contribute toward reaching this goal.

Collaborative field studies are essential, because many questions of process remain and can only be understood at the scale and richness of dynamics found in the natural world. Ecological processes introduce different time scales than do hydrologic processes. Successive rainstorms can provide repeated data sets about how a particular landscape delivers water as runoff, for example. But that same landscape may undergo progressive changes in vegetation composition, when, for example exotic species invade, recovery occurs after a fire, or subtle climate shifts change the competitive edge from some species to others. Such shifts may take years to decades or longer to occur and feed back on the hydrologic and climate system. These slow dynamics call for commitments to long term collaborative studies. The development of inexpensive, easily deployed monitoring devices for ecosystem and hydrologic studies holds the promise of revealing processes over space and time.

One of the greatest challenges faced by Earth scientists is the poor knowledge and inaccessibility of the hydrologically active ground beneath society's feet. In many environments most runoff occurs as subsurface flow. All moisture that gets pulled back to the atmosphere as transpiration as it sustains life is extracted from this near-surface region. Documenting subsurface processes involves the technical challenges of finding ways of "seeing" into the ground and of quantifying the properties of the subsurface, explored further in the following chapter. This documentation should also include analysis of subsurface ecologic processes. Observational tools and models are needed.

Restoration, conservation, and redesign projects to create or regain desired ecosystem services are occurring across a wide range of scale from small seasonal ponds to the entire Mississippi River Delta. Done for practical reasons, these projects are nonetheless invaluable experiments that test the ability to make predictions. Post project monitoring is a critical tool to for learning from these projects and making progressive improvements (NRC, 2006, 2011).

As scientists look ahead, interdisciplinary approaches and perspectives will be needed to gain enough understanding of the interactions between water and life to predict the future states of the Earth system. Many of the research challenges discussed in this chapter exist in the nexus between hydrologic science, ecology, geomorphology, and soil science. Fostering the interdisciplinary scientists and science teams best able to address these research challenges can be ensured by making strategic investments in providing access to inter- and cross-disciplinary research and training opportunities at all stages of professional careers. The magnitude and timing of water delivery shape biological systems but the quality of water is essential to all organisms. The next chapter argues that the ability to have clean water for ecosystems and humans requires understanding, predicting, and managing water quality.

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4

Clean Water for People and Ecosystems

Most living things—humans and ecosystems—depend on availability of clean water. The quality of the planet's waters is changing on time scales of minutes to centuries in ways that are only partially understood. Ensuring clean water for the future requires an ability to understand, predict, and manage changes in water quality.

INTRODUCTION

As the "lifeblood" of the planet and the universal solvent, water transports vast quantities of dissolved chemicals and suspended matter through the biosphere. The concentration of these constituents defines the quality of water and is controlled by naturally occurring and anthropogenic phenomena. Natural variations of the water quality of groundwater, streams, and lakes occur because of geological, climatic, and biological influences. Rain and snowmelt percolate through organic material near Earth's surface, then through the mineral soil, and through the rocks making up aquifers. Surface streams are fed in part by groundwater discharge and the waters also interact with the streambed. In all of these environments, materials dissolve into, or are removed from, the water through reactions that often are mediated by microbes. Water flowing over the land surface also mobilizes sediment, which is then transported in streams and rivers. In this way the hydrologic cycle is intimately linked with all of Earth's element cycles.

Human activities have changed the natural element cycles in many ways. Massive alterations in land use and water allocation, as well as the use of synthetic chemicals, have set in motion a transformation of water quality in many hydrologic basins that, at best, will lead to enhanced water treatment effort or, at worst, to the deterioration of water quality with potentially adverse impacts on human and ecosystem health. In the United States, most of these transformations have been under way since the mid-20th century. In other countries this transformation is just beginning. Yet for many groundwater systems and surface water bodies, the reversal of damages will require a time scale of decades to centuries. For example, groundwater in many parts of the nation is highly enriched in nitrogen, leaving a legacy of nitrogen pollution that, even without new inputs, will take many decades to be diluted by groundwater recharge. Thus, the current quality of any water resource reflects the past as well as ongoing contamination, and water, particularly groundwater, may not become clean even if future sources of contamination are eliminated.

As the global human population grows through this century the demand for clean water will increase. Humans already appropriate more than half of the annual renewable freshwater supply globally, and there are few untapped sources of clean freshwater in the places on Earth where most people live (Postel et al., 1996). Supplying clean water to the growing human population will require much greater water reuse and water treatment than in the past. As societies attempt to increase their standard of living, economic growth will likely exacerbate problems related to water quality and availability, because cleaning water requires energy and energy generation consumes and may contaminate water. The agricultural intensification necessary to feed the growing population and an increasingly urban global population are trends that are likely to further concentrate human and livestock wastes and place additional stress on water treatment systems. The decisions societies make about how to acquire, clean, and dispose of water have enormous impacts on the aquatic ecosystems that are the source of water and the recipient of wastes. The degradation of aquatic ecosystems and the loss of sensitive aquatic taxa can lead to a reduced capacity for natural wetlands, streams, and lakes to trap, store, and transform contaminants. This provides a positive feedback that can further exacerbate water quality problems. Finally, numerous opportunities exist for climate change to impact water quality.

Access to clean water is a political and social problem, but decision makers who are tasked with resolving the problem should be informed by the results of hydrologic research. Science will ensure that the knowledge base necessary to address the challenges of maintaining good water quality where it exists and restoring it when it has been degraded will be available in the future. Research opportunities related to water quality stem largely from a need to know the processes that control the evolution of water quality in both relatively pristine and in heavily impacted environments. The requisite research also spans spatial scales from local to global, and time scales from minutes to decades. Understanding will come through research on the transport and fate of the constituents that dictate water quality of surface and groundwater. Similar to the surge in analytical techniques enabling detection of minute amounts of contaminants in water, the committee anticipates a surge of discoveries from the hydrologic sciences to advance the scientific understanding needed to promote clean water for the planet.

RESEARCH OPPORTUNITIES

Many broad research questions fall within the scope of promoting clean water for the planet and challenge hydrologists and their collaborators in biogeochemistry, environmental engineering, and chemistry. Thus, hydrologic research should pursue more linkages with these disciplines than it has in the past. Feedbacks among the fluxes of water and a variety of elements and compounds are at the core of phenomena that should be understood to advance the Earth sciences. This report presents research opportunities in three broad topic areas. The first area relates to element fluxes in a dynamically variable, highly heterogeneous, connected Earth. The second specifically involves contaminant hydrology and the vexing problems that should be addressed to understand the evolution of water quality. The third focuses on the three important, large-scale drivers of water quality: climate change, energy needs, and agriculture.

4.1. Chemical Fluxes through Complex Environments

Geological materials and surfaces are heterogeneous, which confounds the description of fundamentally important hydrologic processes.

The world is complex and composed of diverse and dissimilar parts, a concept that is referred to as heterogeneity. Heterogeneity presents challenges that scientists grapple with in different ways. Geologists identify and classify rocks by the heterogeneity of their matrix, for example, by grain size or mineralogy. Chemists work with mixtures of substances and characterize compounds by their solubility in one phase of a mixture versus another. Hydrologists grapple with the flow of water through a heterogeneous landscape, both on Earth's surface and in the soils and rocks of the subsurface.

Earth's heterogeneity can be observed at different scales, from pore size in the subsurface, to the irregularity of a river channel, to patchiness of ecosystems—all of which impact the flow of water and, in turn, the movement and concentration of constituents. The flow of water and dissolved or suspended mass fluxes can vary many orders of magnitude over spatial scales ranging from centimeters to kilometers. It is unrealistic to expect that every detail of heterogeneity can be measured and cataloged to further understanding; useful scientific theories, after all, are ones that capture the essence of phenomena simply by setting aside unnecessary complications. Yet, the effects of heterogeneity on hydrological transport and biogeochemical transformation of substances should be generalized to some basic principles so effective water management strategies can be devised. Significant scientific effort has directed toward achieving this goal, yet challenges still remain. With current capabilities, cleanup of contaminated groundwater sites is difficult and not likely to be achieved in a desirable timeframe. This difficulty is, in large part, due to the heterogeneity of the subsurface, which confounds treatment technologies. Finally, heterogeneity leads to the observation that discrete units of landscape are connected by water-mediated transport of matter, energy, and organisms. Understanding the connectivity is one of the goals of hydrologic research related to heterogeneity. Opportunities exist to further understand hydrologic connectivity and its relationship to water quality.

What is the role of subsurface heterogeneity and connectivity in mass transport, and how can it be characterized?

Much of the subsurface contains well-connected pathways of relatively high permeability that constitute only a small portion by volume of porous or fractured media. It is also quite common for most of that portion of the subsurface, referred to as aquifers, to contain substantial volumes of non-aquifer materials, such as silts and clays or unfractured rock, which are not conduits for the flow of water. In the actual three-dimensional world, one need only have a relatively small volume fraction of high-permeability material for that material to fully connect or “percolate” (Harter, 2005). The well-connected, high-conductivity paths cause earlier arrival of contaminants at wells or other receptors than conventional analyses would indicate. Slow mass transfer between these fast paths and the presence of this lower-conductivity media lead to broad dispersion of dissolved constituents. This is consistent with field observations, including the ubiquitous observation that contaminant cleanup by well extraction methods is difficult and often requires decades of pumping.

Thus, progress has been made in understanding the impact of connectivity on the dispersion of chemical contaminants, but it reveals information about connectivity that is of concern. Contaminants are moving faster and are dispersed more widely in the subsurface than was originally thought. Given the importance of groundwater as a source of potable water and in recharging surface water systems, continued improvements in understanding fluxes and transformations in such connected networks should be pursued and will require much new work. Oftentimes, this understanding is derived from research conducted at experiment sites (Box 4-1). Yet the overarching question exists: Can connected networks in the subsurface be characterized to yield a simplified theory, thereby overcoming the heterogeneity problem?

Opportunities exist to develop tools to overcome the heterogeneity challenge. One example involves methods to determine groundwater residence time, the elapsed time from when a parcel of water enters the groundwater system to when it reaches a down-gradient location such as a well or spring. Because groundwater consists of a collection of water and solute molecules that typically have taken very different pathways to the destination, the same groundwater sample can potentially contain water molecules with residence times ranging from years to centuries or millennia. Groundwater age therefore has an age distribution that represents, on the one extreme, the fast flow paths through the high-conductivity, well-connected portions of the system, and on the other extreme, the slow flow paths through the often nonaquifer portions of the system. The age distribution is rich with information about the complexity of the surrounding flow regime, the presence of preferential flow paths, different scales of heterogeneity, and slow mass exchange between the fast and slow parts of the system.

Methods for determining groundwater ages are based on interpreting the presence of dissolved materials and/or associated water molecules at the time they enter the groundwater. The most widely used methods include those based on measuring concentrations of tritium-helium ($^3H/^3He$), chlorofluorocarbon (CFC), and carbon-14 (^{14}C). The key obstacle to measuring the groundwater age distribution is the lack of environmental tracer methods for dating groundwater in the 50- to 3,000-year range (Figure 4-2). What are the new methods that will allow enhanced tracking of water quality by age in this "dating gap window?" Can multiple chemical species, including a variety of isotopes that cover the full range of likely groundwater ages, be used in tandem with an appropriate reactive transport model to infer the residence time distribution in three dimensions for an aquifer system?

Pursuit of these research opportunities will advance understanding of fluxes and transformations in connected, heterogeneous, subsurface networks through field characterization and experimentation as well as new theories. How can water and solute residence time distributions in subsurface hydrologic systems be measured? How can these measurements promote new theories to understand the impact of heterogeneity and connectivity on contaminant distribution? What are the most appropriate models to represent solute transport in aquifers containing different degrees of heterogeneity?

BOX 4-1

Revelations in the Complexity of Flow and Transport Processes

The MADE tracer experiment site at Columbus Air Force Base, Mississippi, is a contaminated site paired with a highly complex, underlying heterogeneous aquifer. This heavily studied, and as a result heavily instrumented, site has provided insights into heterogeneity and connectivity issues at the plume scale over the past 25 years. Research activities have revealed an extreme complexity of flow and transport processes in highly heterogeneous porous media. Existing theories and models have been shown to be incorrect or inadequate, while new ideas and improved approaches are continuously being proposed and developed (Zheng et al., 2011; Figure 4-1).

The key questions and hypotheses emerging from these research activities include the following: Are small-scale preferential flow paths resulting from variations in hydraulic conductivity (K) the primary cause of the observed “nonideal” behaviors in tracer plumes at the MADE site and elsewhere? What are the nature, geometry, and scale of preferential flow channel networks in a highly heterogeneous fluvial aquifer such as that at the MADE site? How are such flow channel networks (and flow barriers) related to the texture, structure, grain size, and facies distribution of fluvial sediments? What is the most appropriate upscaled model to represent solute transport in aquifers containing small-scale, connected, high-K networks without an explicit definition of these networks? How can the parameters for the upscaled model be obtained from readily available field data?

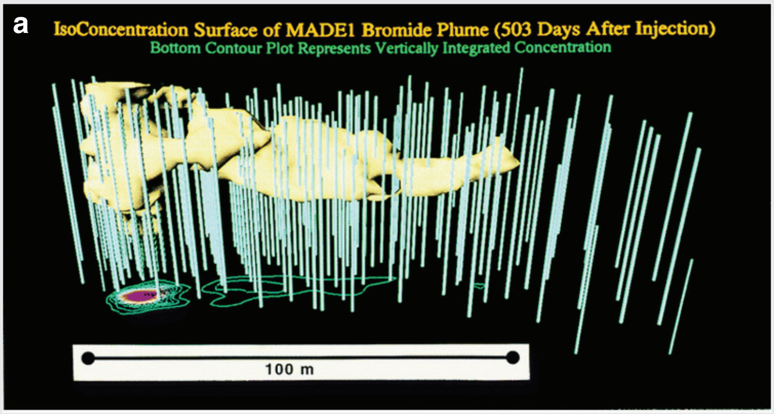
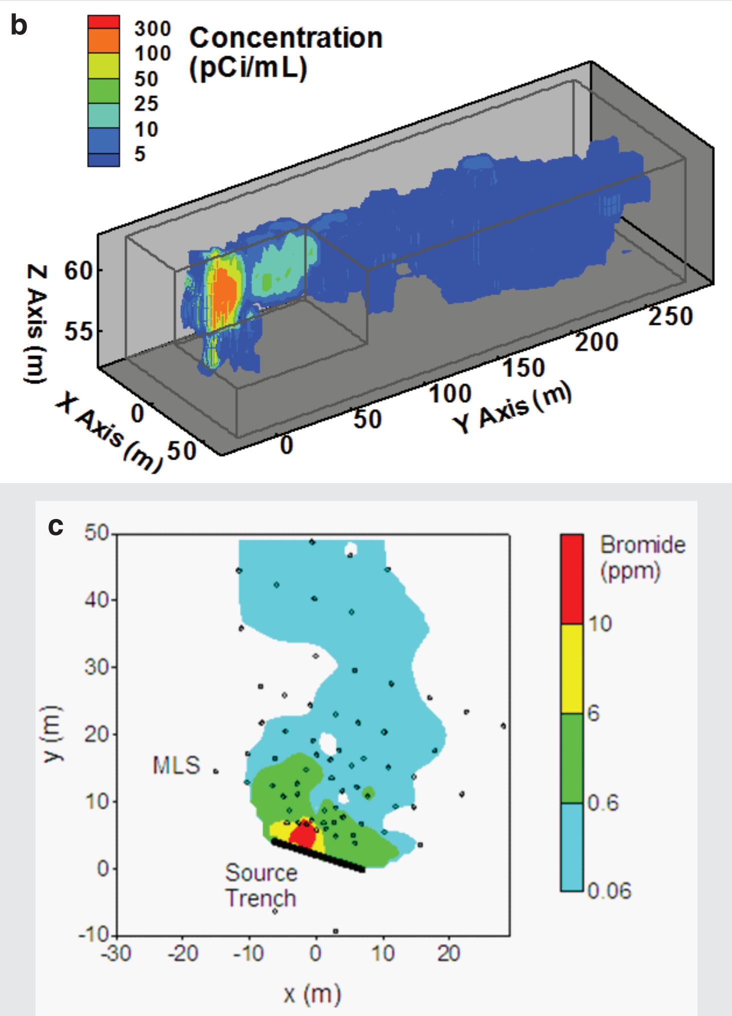


FIGURE 4-1 Observed conservative tracer plumes at the MADE site: (a) bromide plume (concentration in mg/L) at 503 days after 2-day injection from the MADE-1 test; (b) observed MADE-2 tritium plume (concentration in picocurie per milliliter [pCi/ml]) at 328 days after 2-day injection from the MADE-2 test; and (c) observed MADE-3 bromide plume at 152 days after



trench source release. (The two-dimensional contour map is constructed from the peak concentrations at each multilevel sampler location from the MADE-3 test.) All plumes exhibit a highly complex ("non-Gaussian") pattern that cannot be readily described by classical models. SOURCE: Reprinted, with permission, from Zheng et al. (2011). © 2011 by John Wiley and Sons.

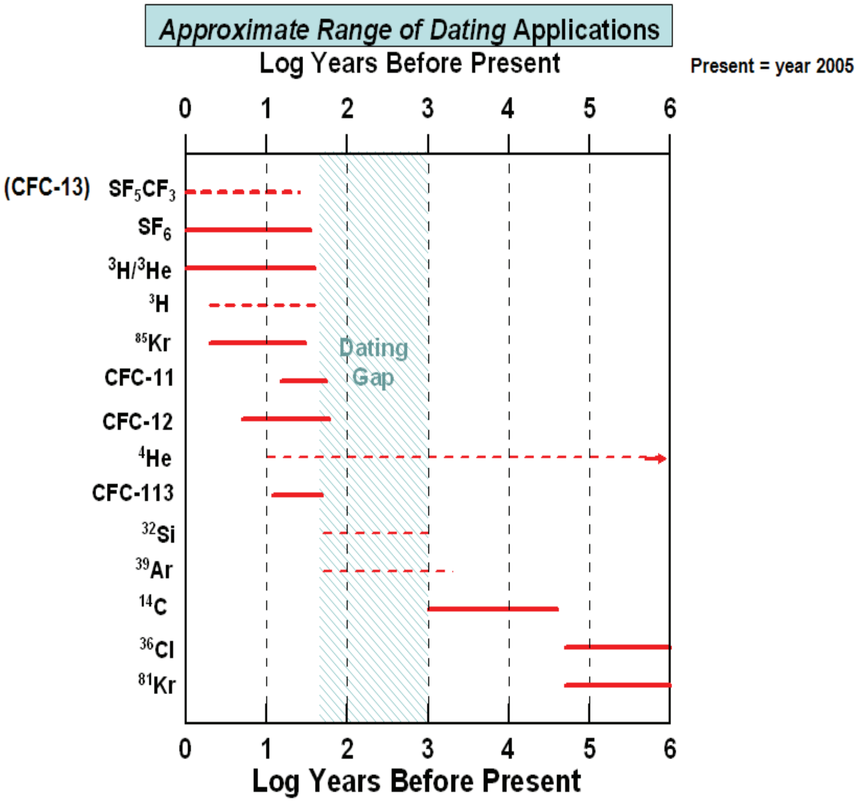


FIGURE 4-2 List of available environmental tracers for estimating water residence time in geologic systems and the “dating gap” for which no reliable methods yet exist for estimating age. SOURCE: Courtesy of N. Plummer, U.S. Geological Survey.

How much of the spatiotemporal heterogeneity in linked hydrological-biogeochemical cycling must be understood to estimate, model, and predict net watershed solute export?

The increasing ability to monitor chemical and biological conditions in real time is revealing previously unknown temporal trends that in turn push the boundaries of process understanding. The more finely watersheds are subdivided and the more frequently hydrologic and biological processes are measured, the more dynamic ecosystem hydrology and biogeochemistry are discovered to be. As hydrologists move into the era of high-resolution data sets, a critical challenge for hydrologists is to determine the data density and distribution necessary to address critical questions about ecosystem-scale biogeochemical behavior. How much detail is needed?

For regional fluxes of water, hydrologic models are typically able to provide reasonable approximations and predictions without highly resolving properties and processes in space and time. For biogeochemically active solutes and elements with significant gaseous forms, coupled hydrological-biogeochemical models often fail to match observations. This is because (1) hydrologic models can match the flux of water without having to accurately approximate pathways and mass exchange between regions of fast and slow flow and (2) representing biogeochemical reaction rates requires reasonable approximations of reactant supply and environmental conditions (temperature, pH, and oxidation reduction potential) along flow paths as well as accurate flow path routing of water. Processes that occur homogeneously across the ecosystem (e.g., organic matter decomposition) will be easier to model and upscale than processes occurring under a more limited set of conditions (e.g., denitrification, which occurs only under conditions of low oxygen, high carbon, and high nitrate). For heterogeneously distributed biogeochemical processes, measures of whole ecosystem rates provide little information about where and when the process occurs.

There can be great spatial and temporal heterogeneity in the availability of nutrients and the extent of hydrologic connectivity within ecosystems. Because of this variation, there are places and times within ecosystems that can play disproportionately large roles in driving whole-ecosystem biogeochemistry. For example, riparian zones that receive materials from the surrounding uplands and that are more highly hydrologically connected to streams than the rest of the catchment tend to have heightened rates of nutrient transformations. Although scientists conceptually recognize the likely importance of these rare moments and locations for enhanced biological activity, in practice it has been challenging to define, locate, and monitor these ecosystem control points. The increasing ability to map and monitor hydrology, chemical concentrations, and biological activity in real time is revealing previously unknown spatiotemporal hydrologic and biogeochemical dynamics (Box 4-2) that in turn push the boundaries of process understanding. What variables control the occurrence and magnitude of hot spots in terrestrial, riparian, and hyporheic zones? Can knowledge about the joint distribution of organic carbon and fast flow paths be used to infer the major control points for ecosystem biogeochemical reactions? How do human interventions on the landscape change hydrological connectivity and therefore the spatial distribution of hot spots?

BOX 4-2
Understanding of the Correlated Variation in Hydrologic Science and Biogeochemistry through Technological Innovations

Technological innovations are providing an unprecedented understanding of the spatial and temporal covariation in hydrology and biogeochemistry. At landscape scales, remote sensing technologies effectively capture hydrologic variation in space and time. For example, synthetic aperture radar derived vegetative cover and inundation for a reach of the Solimões River in the central Amazon Basin, Brazil, is shown in Figure 4-3. On a much smaller scale, microelectrode profiles illustrate the variability of oxygen, iron, and manganese concentrations in co-located sediment profiles (Figure 4-4). Measurement techniques have provided new insights into soil stream interactions, as well. For example, dissolved carbon dioxide (CO_2) concentrations for a peatland stream vary over the course of a storm hydrograph (Figure 4-5). Finally, high-frequency in situ sensor arrays in Ichetucknee River, Florida show the close relationship between nutrient cycling and metabolic activity (Figure 4-6).

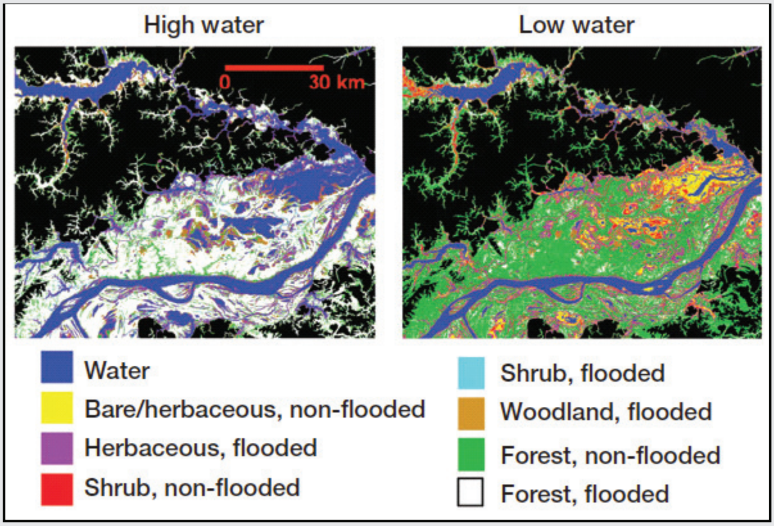


FIGURE 4-3 Landscape-scale remote sensing technology showing vegetative cover and inundation for a reach of the Solimões River in the central Amazon Basin, Brazil. SOURCE: Reprinted, with permission, from Hess et al. (2003). © 2003 by Elsevier.

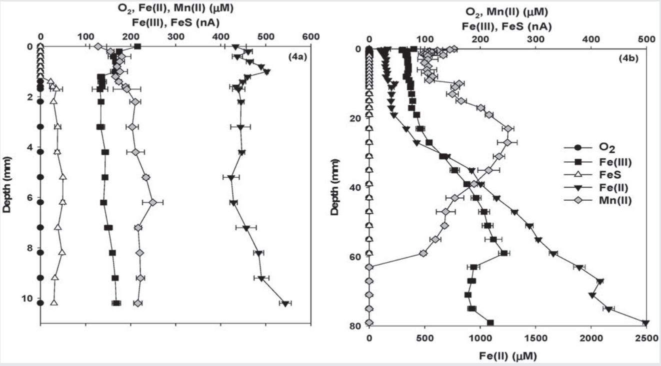


FIGURE 4-4 Voltammetric profiles indicate significant variability in speciation in wetland soils 2 cm apart in sediment cores collected on the same day in Jug Bay, Maryland. SOURCE: Reprinted, with permission, from Ma et al. (2008). © 2008 John Wiley and Sons.

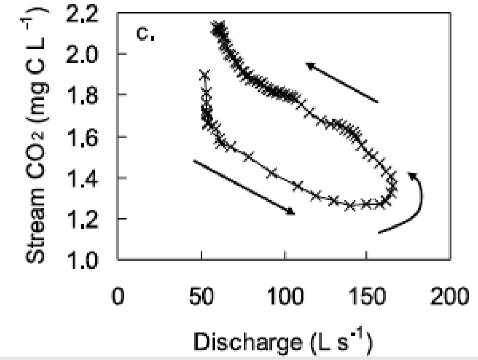
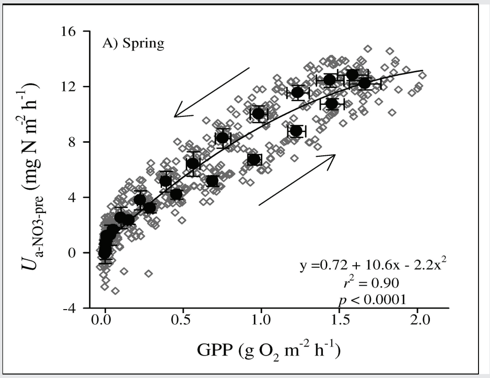


FIGURE 4-5 Variability of dissolved CO_2 concentrations (mg C L^{-1}) for a peatland stream over the course of a storm hydrograph (discharge in L s^{-1}). SOURCE: Reprinted, with permission, from Dinsmore and Billett (2008). © 2008 by the American Geophysical Union.

FIGURE 4-6 Diel covariation in gross primary production (GPP in g O_2 m^{-2} h^{-1}) and nitrate uptake (autotrophic N assimilation or uptake as $U_{a\text{-}NO3\text{-}pre}$ in mg N m^{-2} h^{-1}) rates in the highly autotrophic Itchetucknee River, Florida. The line is best-fit least-mean-square regression on individual observations (see Chapter 1, Figure 1-4 for the in situ observations used to probe this coupling). SOURCE: Reprinted, with permission, from Heffernan and Cohen (2010). © 2010 by the American Society of Limnology and Oceanography.



How do river networks interact within the channel and upland areas to organize sediment composition and mass flux, and in turn, river biogeochemistry and water quality?

Sediment produced from hillslopes travels into and through the river network both spatially and through time, swept in pulses by floods, sorted hydraulically, and changed in size and composition by abrasion and other mechanisms. Enhanced sediment input into aquatic systems can impact light penetration and hence photosynthesis and the health of biological habitats. Sediment carries with it constituents that are dispersed in the landscape, rivers and floodplains, and affect water quality and biogeochemistry. Recent research has highlighted that bedload sediment composition and mass flux in a river basin might be set by not only the channel network structure, but also, to a large degree, the sediment size and composition supplied from upstream hillslopes. This dynamic connectivity between channels and their surroundings is not unique to erosional systems; in fact, it is even more pronounced in net depositional systems such as deltaic networks. For example, the hypsometric, or height measurement, analysis of the land-building field site at Wax Lake Delta, Louisiana, displays the intricate connection between land, water, and plant communities that dynamically changes under natural and human influences (Figure 4-7).

Understanding the dynamic co-evolution of channels and their surroundings is key to improving prediction of stream biogeochemistry, water quality, and ecosystem integrity in a landscape. Such understanding is also crucial in developing minimal complexity predictive models, which capture the essential components of the system and can be used as management tools to explore system response to perturbations such as climatic change (e.g., storm intensification or sea level rise) or anthropogenic stresses (e.g., land-use changes). New observations, such as high resolution topography and vegetation cover from Light Detection and Ranging (LiDAR), as well as new geophysical monitoring techniques for subsurface flow characterization and water and sediment dating offer new opportunities for advancing understanding of water-mediated transport of environmental fluxes through landscapes.

Many open research questions exist, and the committee provides here only a few examples. What is the relative role of nonfluvial (hillslope or subsurface) versus fluvial (channel network) transport pathways in determining water quality, biogeochemistry, and river ecosystem health? Are there places in the landscape where accelerated changes or amplifications occur and where observations and focused understanding would do most good? Under what conditions do systematic changes in hydrologic regimes (altered flood cycles, prolonged droughts) or land use changes (agricultural drainage, fires, etc.) bring the coupled water-sediment-biota system to new

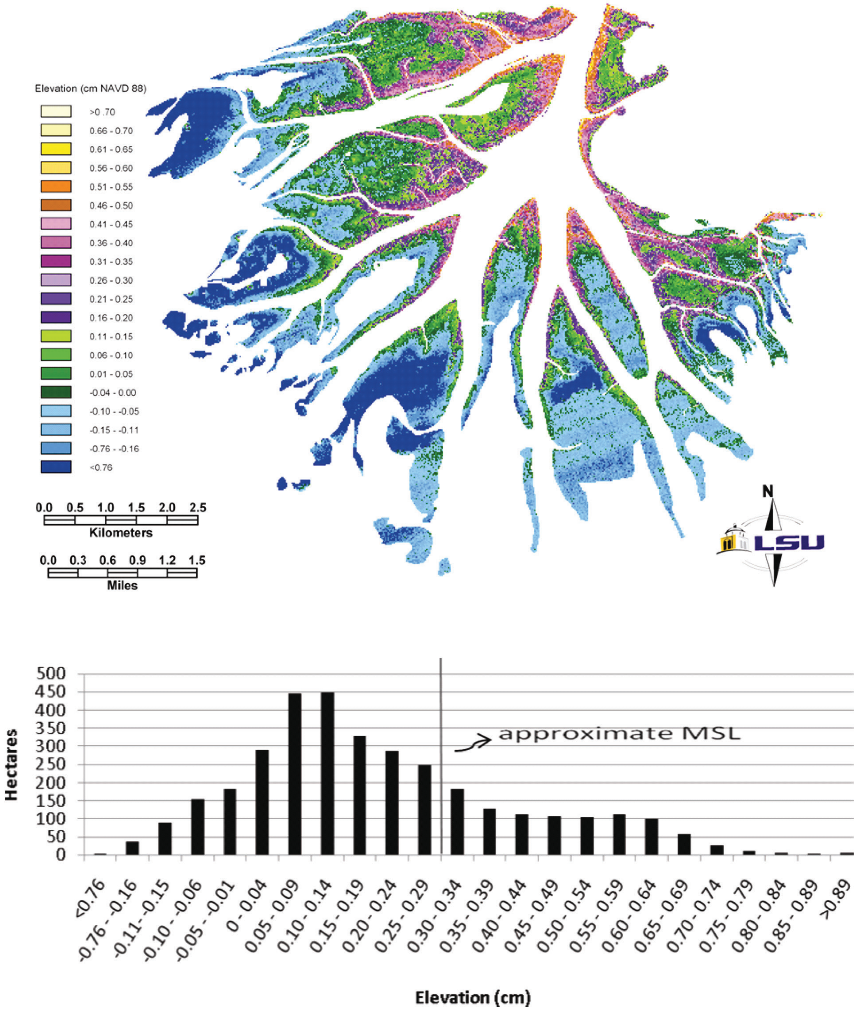


FIGURE 4-7 The terrain complexity in a deltaic system of channels modulates complex interactions between water, earth, and biota for which predictive models are lacking. This picture shows the elevation analysis of LiDAR data from the Wax Lake Delta, Louisiana, with the distribution of total area (hectares) within 5-cm elevation classes. The elevation is corrected to cm NAVD 88 and paired with an estimate of mean sea level (MSL). Analysis of plant community types overlaid on this elevation data is needed to advance predictive understanding of delta island plant community structure. SOURCE: Image courtesy of Elaine Evers, Louisiana State University.

equilibrium states or to states that are unstable and thus prone to large shifts even under small perturbations?

How can transport and transformation of constituents through complex media be better described mathematically?

The broad range of space and time scales of transport through a heterogeneous world challenge existing predictive models and has prompted development of new classes of predictive models through generalization of standard models that have been used for decades but have essentiallyignored heterogeneity. For transport in surface waters, new ideas and theories have recently been put forward to characterize a range of processes: from particle transport in a single stream, to sediment and water transport on hillslopes, to dynamic transport on erosional and depositional river networks.

Research has shown that mineral heterogeneity is important to controlling field-scale reactive transport under many field conditions of interest (Allen-King et al., 2002). Development of models that include processes at all scales relevant to field-scale reactive transport, including statistically quantifying observed mineral heterogeneity for these models, remains a challenge. This challenge motivates a variety of research needs including appropriately quantifying basin-scale mass transfer among different geologic media, increasing computational efficiency, and dealing with details of biogeochemical reactions (Fogg and LaBolle, 2006). Quantifying the uncertainty of these models represents an additional major hurdle. Specific research questions of interest include the following: Do physically based models of transport give rise to the emergent patterns of space-time flux variability observed in nature? How can these new classes of models be tested from observations, and how can their parameters be estimated? What experiments are needed to verify and further advance these new theories of transport?

4.2. Earth's Evolving Water Quality Profile

The water quality profile of the planet is evolving as new contaminants are introduced to the water cycle and old contaminant use continues.

As contaminants move through an irregular but interconnected world, Earth's water quality profile evolves in space and time. Discharge of contaminants has disturbed the planet's water chemical composition and raises the question: How widespread and severe is the deterioration in the planet's water quality? The idea that clean water is accessed only upstream from human activity has hardly ever proven to be a useful concept and is now particularly questionable given that "there is no upstream anymore." Some contaminants have spread globally through the water cycle. Even after years of concern about a variety of contaminants, some problems continue to worsen, and this trend is expected to continue in the future.

The existence of "classic" contaminants—arsenic, lead, chloride, and many others—and knowledge about their behavior in and impact on the environment is relatively well established, although there are open research questions related to the bioavailability and transport of these contaminants. The content of nitrogen and phosphorus in rivers and streams worldwide has increased as a consequence of human activities (Nilsson and Renöfält, 2008). It is now estimated that as many as 77 million people in Bangladesh—approximately half the country's population—and perhaps many more in other portions of southeast Asia living on river valleys draining the Himalaya are afflicted with arsenic poisoning from drinking shallow groundwater containing naturally high concentrations of arsenic from the aquifer materials (Figure 4-8). Although the situation in Bangladesh has

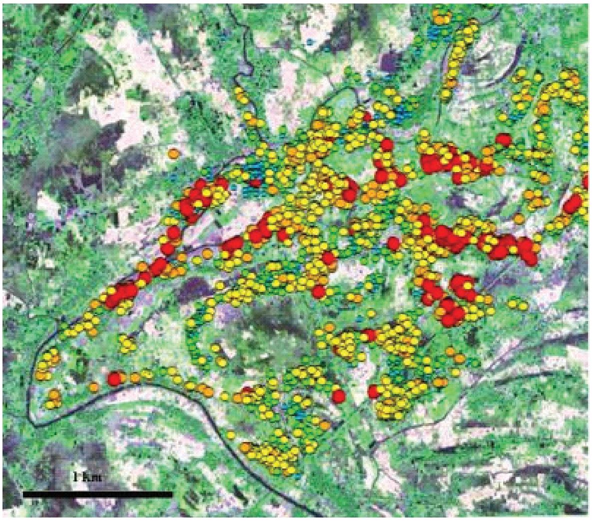


FIGURE 4-8 Arsenic contamination in the groundwater of the floodplains of central Bangladesh. Symbols are graduated in size and color to indicate higher arsenic concentration. Arsenic concentration varies spatially because of complex interrelationships among hydrologic flow paths, sediment structure, organic carbon, and pumping. SOURCE: Image courtesy of Beth Weinman, Vanderbilt University. Available online at http://sitemason.vanderbilt.edu/site/kFvWDK/Research [accessed August 6, 2012].

received the most attention because of the scale of this human tragedy, arsenic contamination is a global problem that affects water supplies in the United States as well as other locations. *Opportunities in the Hydrologic Sciences* showed the dramatic increase in chloride flux in Europe's Rhine River from 1890 to 1990, a phenomenon closely tied to the use of sodium chloride as road deicing salt. This increase in chloride flux continues today, for example, in the northeastern United States where in some cases stream water concentrations of chloride have increased significantly since the 1960s (Figure 4-9). Extrapolations suggest that baseline values of chloride in some streams will exceed the accepted level for human consumption and the toxicity level to many freshwater organisms in the future.

The recent advancements in analytical techniques mentioned in Chapter 1 have allowed for identification of a suite of other contaminants in an alarming number of freshwater bodies about which much less is known. These contaminants of emerging concern include pharmaceuticals, engineered nanoparticles, and additives in personal care products, to name a few. Their presence in the water cycle can be traced to numerous point and nonpoint sources such as wastewater treatment systems, septic systems, regulated and unregulated industrial discharges, manufacturing processes, large-scale animal feeding operations, combined sewage overflow, and urban runoff. The chemical properties of these contaminants often promote transport (e.g., high solubility) and chemical transformation (e.g., susceptibility to oxidation) in the aqueous environment. The list of contaminants of emerging concern known to be present in natural waters is quite large, ranging from hormonally active agents to caffeine. With development of new chemicals and their subsequent introduction to the water cycle, this list continues to grow.

Much of the fundamental work mentioned in the section above on Chemical Fluxes Through Complex Environments is critical for understanding the evolution of the water quality profile. Yet pursuing answers to other questions will promote scientific understanding of how the water quality profile evolves in space and time and how contaminants interact with hydrologic processes and impact stream ecosystems.

How do hydrologic processes impact contaminant fate and, in turn, affect the evolution of water quality?

In the United States, much of the groundwater used for the public drinking water supply is from deeper portions of the aquifer systems where the groundwater is too old, decades to centuries to millennia, to contain significant anthropogenic contamination. However, shallow, poorer-quality groundwater is typically moving downward through largely unknown pathways and increasingly contaminating deeper groundwater at largely

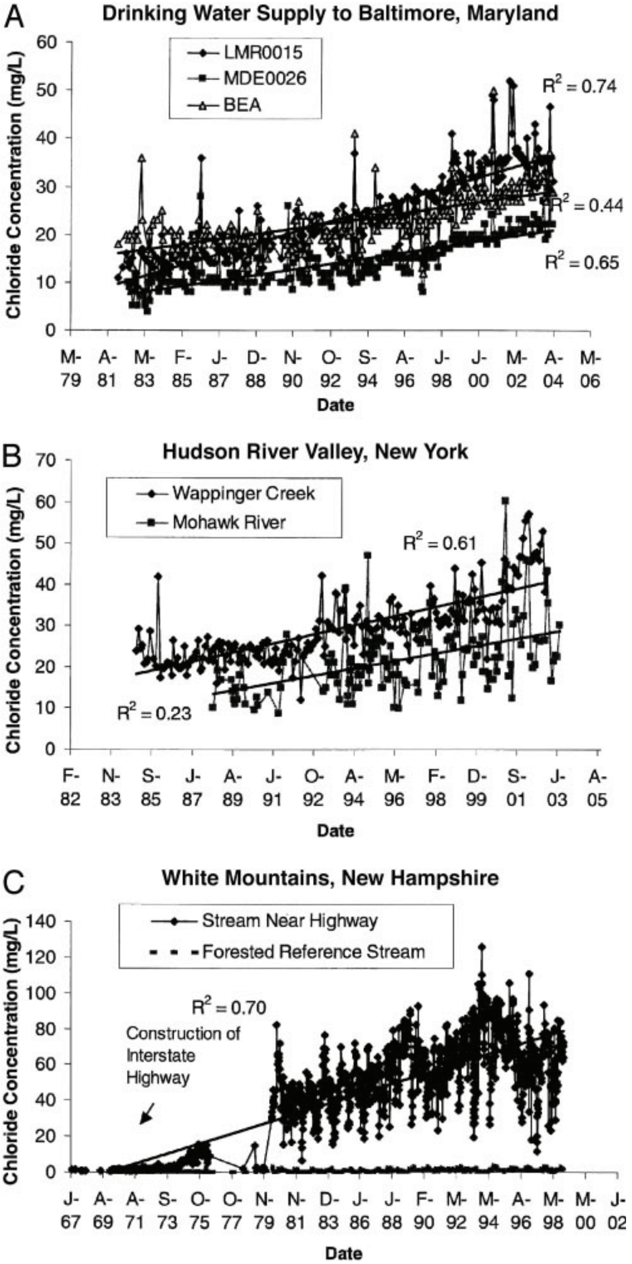


FIGURE 4-9 Increase in the concentration of chloride in streams and rivers in rural areas in the northeastern United States. SOURCE: Reprinted, with permission, from Kaushal et al. (2005). © 2005 by National Academy of Sciences, U.S.A.

unknown rates. Thus, problems with contaminants in groundwater may occur years or decades in the future making it difficult to muster public or political concern. The groundwater quality in some basins may be nonsustainable; if left unchecked over decades to centuries contamination can theoretically lead to regional degradation of entire groundwater basins, the quality of which is linked to surface water. Yet, work to understand, monitor, and model the relevant phenomena to predict long-term sustainability of groundwater quality mostly lies ahead (Fogg and LaBolle, 2006). How is the contaminant signature in deeper groundwater changing over time?

It is hypothesized that the conversion of grasslands and forest to row crop agriculture has decreased evapotranspiration and therefore increased recharge in these landscapes, which has led to increased base flow contributions to the streams and rivers in the basin (Zhang and Schilling, 2006). Along with this increase in groundwater has been an increase in the flux of chemical weathering products such as bicarbonate, the dominant form of inorganic dissolved carbon in most rivers (Figure 4-10). It has been suggested that approximately half of the increase in bicarbonate concentration in the lower Mississippi River over the past 50 years is due to the alteration of the hydrologic system brought about by conversion to agriculture (Raymond et al., 2008). How do anthropogenic changes in land use alter water flow paths that in turn impact other elemental fluxes and water quality?

On a much smaller scale, some progress has been made on tracking the chemical transformation and fate of contaminants of emerging concern because of, in large part, advances in analytical techniques. It is known that some contaminants of emerging concern transform by light-driven chemical reactions in the upper portions of the water column, some contaminants are hydrophobic and immobilized in the surrounding substrate, and some are transformed by microbial processes. Some chemical reactions are often enhanced by naturally present constituents like iron or dissolved organic matter, accelerating transformation of these compounds. These chemical transformations generate an entire suite of "second-generation" contaminants of emerging concern, the scope and impact of which are largely unknown. For example, dioxins, one of the most toxic synthetic organic compound classes known, have been detected in Mississippi River sediment. This was attributed to the existence of a chemical precursor triclosan in the natural environment, perhaps most widely used in the formation of liquid hand soaps, which is known to form dioxins when irradiated by sunlight (Buth et al., 2010).

Relevant questions ripe for interdisciplinary research between hydrologists, chemists, and environmental engineers include the following: What is the chemical "end game" for a given contaminant depending on flow path? What is the mobility (i.e., transformation and fate) of unstudied

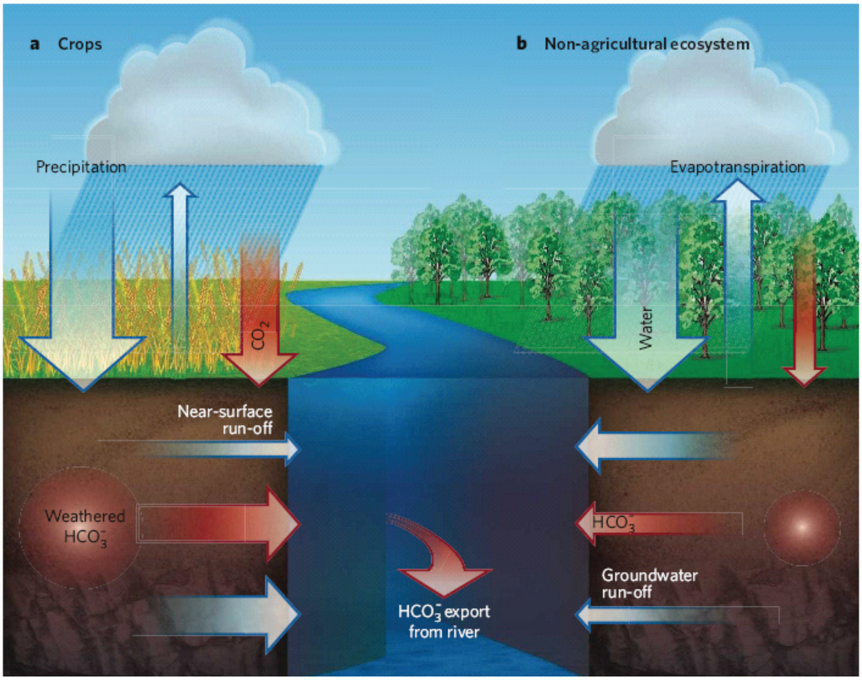


FIGURE 4-10 Even with a similar precipitation rate, soil type, and soil condition, certain agricultural practices result in greater groundwater runoff and less evapotranspiration in comparison to nonagricultural ecosystems. The increase in groundwater runoff leads to larger bicarbonate (HCO_3^-) exports to rivers. SOURCE: Reprinted, with permission, from Mayorga (2008). © 2008 by the Nature Publishing Group.

contaminants of concern? Which contaminants of emerging concern are bioavailable and which may bioaccumulate, and how do these processes interact with hydrologic processes to affect the evolution of water quality? What are the typical suites of contaminants to which humans and ecosystems are commonly exposed? How will the evolution of the water quality profile differ in urban and rural environments with different hydrologic and biogeochemical drivers?

What are the relationships between contaminants and human and ecosystem health and how can deleterious effects be avoided in the future?

Alterations in water supply rarely occur without concomitant changes in water chemistry and water temperature. The "replumbing" of the water cycle has disturbed the link between flow regime and water quality, causing a shift in water quality beyond natural variability that has become especially profound since the industrial era (Nilsson and Renöfält, 2008). The timing of contaminant delivery to surface water and groundwater and the combined effects of flow alteration and contaminant loading have not been adequately addressed by the hydrologic community. Better understanding and prediction of the links between contaminants and hydrologic alteration and the impacts on water quality (and in turn on humans and aquatic ecosystems) are needed. This knowledge will inform changes in policy that will be needed to protect water quality in the future. How do alterations in water flow paths affect temperature and contaminant regimes of freshwater ecosystems? What maintains thermal and chemical refugia in freshwaters, and how can they can be protected, preserved, and restored?

Exploration of diel (24-hour) signals in natural waters yields insight into the intricate linkages among hydrological, biological, and geochemical processes (Figure 4-11). For example, variations in dissolved oxygen concentrations and pH in streams and rivers are driven by the biological processes of photosynthesis and respiration. These diel variations in stream metabolism may in turn play significant roles in controlling the dissolved metal concentrations in solution. Research in a wide variety of streams and rivers has discovered substantial diel variation in potentially toxic metals, where dissolved cationic species, such as zinc, cadmium or manganese, have their highest dissolved concentrations shortly before sunrise, while anionic species, such as arsenic, have their highest dissolved concentrations in the late afternoon (Figure 4-11). The timing of the maximum and minimum dissolved concentrations with light and dark cycles has significant implications for the determination of fluxes as well as potential biological uptake. What biogeochemical processes, such as variations in photosynthesis and respiration, affect other potential contaminants?

Hand in hand with the issue of contaminants of emerging concern is the increasing role that wastewater effluent plays in streamflow in arid regions and even nonarid regions during periods of low base flow. Under these circumstances, wastewater effluent in urban environments constitutes the dominant source of streamflow (Brooks et al., 2006). Thus, in such streams the chemical composition can be very different from that of natural waters. How do these differences translate into effects on aquatic ecosystems? For example, the occurrence of intersex fish has increased in surface waters throughout the United States (Hinck et al., 2009), and the presence of human estrogenic compounds (as well as other anthropogenic substances) have been implicated for this phenomenon. Thus, streams that receive significant amounts of domestic wastewater effluent with trace levels of human estrogenic substances could have long lasting deleterious effects on aquatic ecosystems.

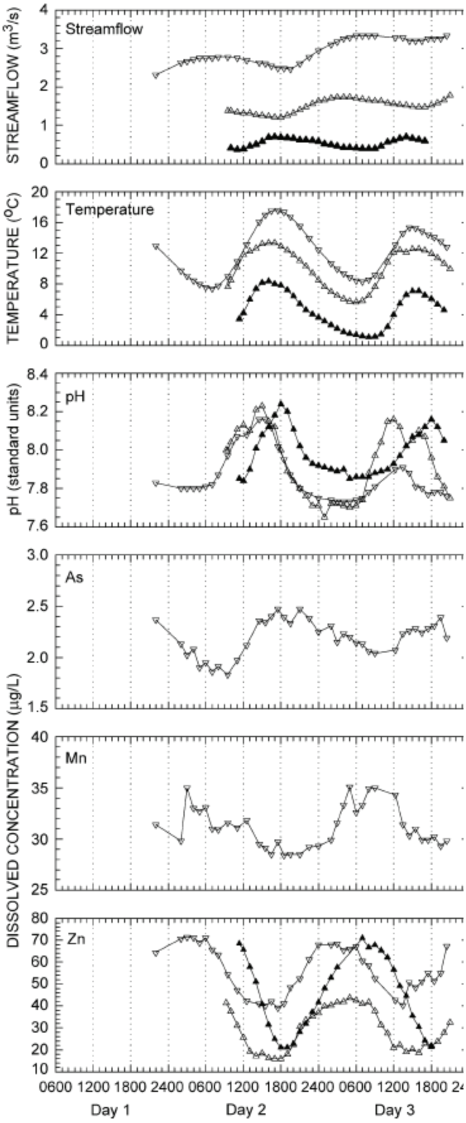


FIGURE 4-11 Diel (24-hour) cycles in streamflow, temperature, and pH, and dissolved arsenic (As), manganese (Mn), and zinc (Zn) concentrations during snowmelt runoff episodes. Episodes were sampled during an early snowmelt-runoff (March 22-23, 2001; closed triangles) and a late snowmelt-runoff (April 26-27, 2001; open triangles and May 23-25, 2011; open inverted triangles) at Prickly Peak Creek, Montana. SOURCE: Reprinted, with permission, from Nimick et al. (2005). © 2005 by Springer Science + Business Media.

A more detailed understanding of water quality continues to emerge from the increasing sophistication of chemical analytical instrumentation and includes detecting contaminants at increasingly lower concentrations as well as new contaminants. Yet, when is the risk from the presence of these constituents so small that it is negligible for all practical purposes? Merging information about the relationship between hydrologic flux and contaminant concentration with risk assessment is critical. What are the contaminant dilution ratios resulting from hydrologic flux, and how should the findings inform risk analysis?

4.3. The Future of Water Quality in a Hot, Flat,[1] and Crowded World

As Earth's human population moves toward 9 billion, as resource use intensifies, and as climate changes, maintaining adequate water quality will rely on new knowledge.

The final layer of complexity in the water quality picture involves the large-scale drivers of water quality. Much conversation revolves around Earth's growing population and demographic change. Intellectual leaders debate questions about how the world should deal with the corresponding intensification of resource use and the impact of climate change. The amount of food required to feed the projected population of 9 billion is staggering—and currently many people go hungry. Similarly, the energy required for transportation, to generate electricity, or to provide clean water for 9 billion people is enormous. And all of these demands should be considered against the backdrop of a changing climate, providing yet another challenge to maintaining adequate water quality for humans and ecosystems.

The layers of complexity in a hot, flat, crowded world are daunting. The world will need scientific knowledge to even begin to deal with these issues. The hydrologic research community has an obligation to tackle the water quality questions embedded within these large-scale drivers.

How do changing flow paths as a result of urbanization correspond to changes in water quality?

Currently, about half of the global population lives in urban areas. As global urban migration continues, this is expected to increase to 60 percent

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[1] The term "flat," coined by the author Thomas Friedman in his books *The World is Flat* (2005) and *Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America* (2008), is used to describe a new era of globalization that allows people and entities around the world to compete, connect, and collaborate.

by 2030 (UN, 2006), which will have impacts on the environment. For example, the increase in impervious surface area associated with urbanization slows evaporative cooling, allowing surface temperatures to rise higher than in rural areas. Impacts on the urban hydrologic cycle also exist; it has long been recognized that the increase in impervious surface area leads to a decrease in infiltration and an increase in runoff, thereby changing the hydrologic response of streams.

The recognition of water quality problems associated with urban development has influenced engineering design in the 21st century. Incorporation of "green" infrastructure into the engineering of cities has become prevalent, whereby effects of stormwater and impervious surfaces are mitigated through designs that attempt to mimic the natural hydrologic cycle and management of stormwater on a watershed scale (NRC, 2008). Practices include promoting infiltration of stormwater such as removing hardened surfaces and regreening urban lands; incorporating grass swales, rain gardens, and green roofs into landscape design; using pervious paving materials; and installing subsurface storage where infiltration practices are not possible. An opportunity exists to probe the geochemical phenomena associated with changing urban flow paths, i.e., stormwater.

Knowledge exists in this area. For example, a smaller percentage of atmospherically introduced contaminants are retained in urban landscapes compared to forested ones. As a result, chemical concentrations of nitrogen and metals are higher in urban streams (Figure 4-12). This lack of retention of contaminants in urban drainages can have effects on downstream aquatic ecosystems and potable water supplies. Future increased water demand in urban systems will exacerbate this problem. What are the impacts of urbanization on hydrologic connectivity and, therefore, water quality? How do urban management practices, for example, urban stormwater management, impact hydrologic connectivity, water quality, and ecosystem health?

What new hydrologic knowledge is needed to enable agriculture and silviculture to be sustainable with respect to water quality?

The role of agriculture in water quality continues to be a major global problem. As the global population increases, the need for food and fiber will increase, leading to the need to convert more marginal land to agriculture and to increase agricultural production per unit land area. In the latter case, increased fertilizer usage will increase nutrient fluxes, especially fixed nitrogen compounds, into both groundwater and surface water systems. These nonpoint sources enhance eutrophication and nuisance algal blooms in water bodies locally, regionally, and even far afield as demonstrated by increased hypoxia in the Gulf of Mexico due to input of nutrients from

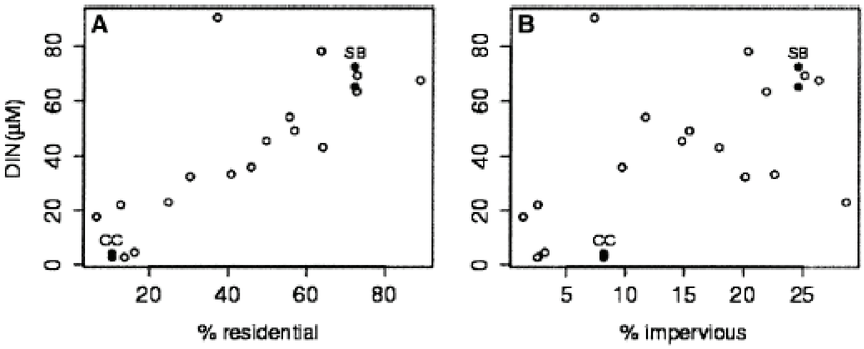

FIGURE 4-12 Increasing annual flow weighted dissolved organic nitrogen concentration (DIN, µM) with increasing residential area (A) and impervious surface (B). SB and CC represent two catchments of contrasting land use (heavily residential and heavily forested). SOURCE: Modified, with permission, from Wollheim et al. (2005). © 2005 by Springer Science + Business Media.

Mississippi River waters derived primarily from row-crop agriculture in the Midwest.

In addition to introducing contaminants into the environment on a landscape scale, irrigated agriculture also has a large demand for water, which in turn often leads to groundwater overdraft. Under predevelopment conditions, the groundwater systems flowed from recharge areas to natural discharge areas, providing an exit for dissolved salt. However, when overdraft occurs and the pumped groundwater is reapplied to the land for irrigation, a closed hydrologic basin is potentially created whereby shallow groundwater of lesser quality (for example, elevated salinity) eventually makes its way to the pumping wells, only to be withdrawn and reapplied to the land, resulting in further concentration of salts and nutrients. Such a closed system in agricultural basins such as the San Joaquin Valley of California may lead to long-term salinization of groundwater, which will eventually render the groundwater unsuitable for irrigation and most other uses. In certain environments, conversion of natural landscapes to agriculture also can impact groundwater due to groundwater rise. If the native vegetation is replaced with less water consumptive crops, then the subsequent rise in the water table can solubilize previously accumulated salts, increasing groundwater salinity, mobilizing nitrate, and salinizing soil.

Efforts to ensure global food security will lead to changes in practices that will need to be assessed, which underscores the importance of addressing critical research questions. What are the hydrologic and water quality implications of changes in crop patterns and rotations? What are the possibly nonlinear feedbacks between irrigation water quality and plant productivity, and how are these affected by management of the hydrologic regime? As the approach to "peak phosphorus" leads to resource restrictions, it will become necessary to pervasively employ nutrient recycling (for example, recovery and use of nutrients from municipal and other waste products). What are the water quality implications related to the use of different fertilizer forms?

How can the hydrologic sciences inform solutions to the "water-energy nexus"?

Water and energy are mutually dependent resources. Increased energy consumption will lead to increased water consumption and water availability challenges throughout the globe (explored in Chapter 2). Yet, the "water-energy nexus" has the potential to impact water quality, as well. Water is needed in the production, refinement, or distribution of a variety of energy sources, and when water is used in this manner there is an impact on water quality. For example, 90 percent of all of the electricity used in the United States is generated by steam, which must then be cooled to condense and reuse or returned to waterways (Averyt et al., 2011). Power plant cooling uses approximately 30 percent more water than is used in irrigation in the United States, and although the water use is mostly nonconsumptive, return flows are warmer than initially extracted, impacting aquatic ecosystems (Averyt et al., 2011). The scope of the water-energy nexus is broad indeed given the need for water and energy for 9 billion people; changes in the thermal regime of aquatic ecosystems is just the beginning. How will the increasing need for energy impact the planet's water quality?

Extraction techniques to obtain a variety of carbon-based fuels have a long history of causing adverse water quality impacts. For example, drainage of acidic waters from coal mines (acid mine drainage) has long plagued coal-producing regions. Many open questions remain related to the impacts of energy production on water quality. One current example relates to the development of natural gas from deep shale beds. Hydraulic fracturing, a technique that produces natural gas otherwise locked in organic-rich shales, involves injecting water and chemical additives into shales at high pressure. The potential environmental impact of hydrofracturing has been a contentious topic. Accidental releases of contaminants into aquifers have been documented, likely because of improper well construction. Disposal of flowback water from wells in surface disposal ponds also has been implicated in water contamination. What research on hydrogeological implications of hydrofracturing and on the chemical composition of injection fluids and their interaction with natural minerals is needed to properly inform the public debate?

Marine and hydrokinetic energy—energy from waves, tides, and currents in oceans and so forth—generates power by harnessing the natural flow of water without using a dam, a diversionary structure, or an impoundment. While in its infancy, this energy source has potential; marine and hydrokinetic energy could provide almost 10 percent of the U.S. electricity demands, a step toward the 2020 mandated requirement of 20 percent renewable energy by electric utilities in the United States (American Clean Energy and Security Act of 2009). Yet, the environmental effects of marine and hydrokinetic energy are far from understood. It is known that this technique will reduce water velocities in the vicinity of the project, as well as increase water surface elevations and decrease flood conveyance capacity at larger scales (Bryden et al., 2004). As this technology develops (Figure 4-13), research efforts to provide the scientific understanding of how harnessing the natural power of water disrupts the water cycle and alters water quality will become a priority. What are the related changes in

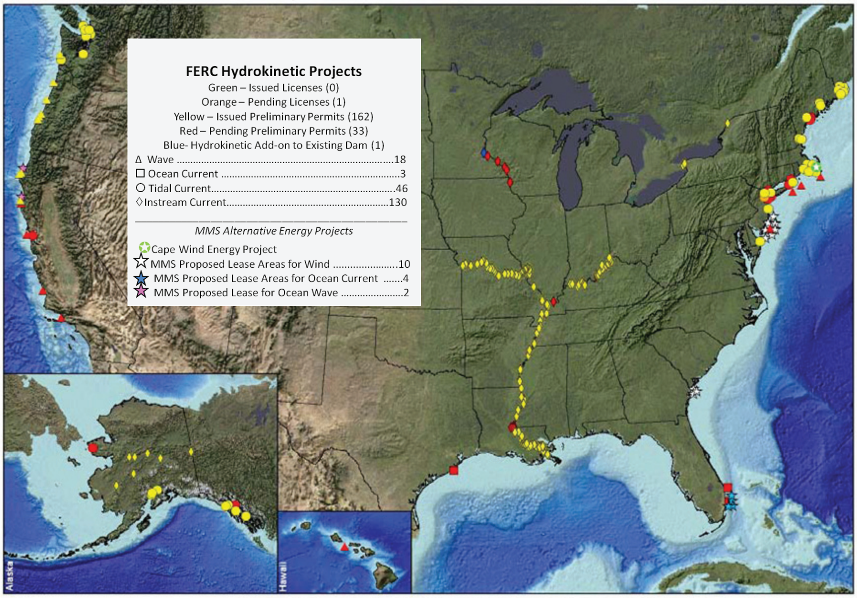

FIGURE 4-13 Federal Energy Regulatory Commission (FERC) marine and hydrokinetic alternative energy projects in the United States. The pressure for advancing marine and hydrokinetic energy is running faster than the knowledge needed to ensure that these projects are not adversely affecting the environment in the near or long term. SOURCE: NOAA Fisheries Office of Habitat Conservation, February 11, 2009.

natural flow paths, which could in turn lead to altered water quality and effects on the aquatic food web? What are the long-term effects in estuary and lagoon inlets of, for example, changing wave height?

Solutions to offset the buildup of carbon from carbon-based fuels also are being pursued. Carbon sequestration, processes to remove CO_2 from the atmosphere, is increasingly looked to as a means of mitigating the impact of global warming. Carbon can be stored in various forms: liquid in the oceans, gas in deep geologic formations, or solid using chemical reactions to produce stable carbonates. Carbon sequestration processes also can take a variety of forms, from injection of carbon into underground reservoirs to development of tree plantations. But like with any retooling of the natural environment, the consequences of these efforts can be surprising. For example, semipermanent, biological carbon sequestration through extensive tree plantations will reduce streamflow and impact water quality. Carbon sequestration in deep geologic formations has the potential to affect groundwater quality. What are the water quality tradeoffs associated with various carbon sequestration strategies? What data are necessary to inform risk analysis models assessing the impact of carbon sequestration techniques on water quality?

What might be the effects of climate change on freshwater quality?

Understanding the impact of climate change on water *availability* has received particular attention. Far less attention has been paid to the impact of climate change on water *quality* and, as a result, far less is known. Numerous opportunities exist for climate change to produce new regimes that impact water quality, from increasing sediment, chemical, and pathogen loading in runoff to saltwater intrusion threatening the quality of coastal groundwater supplies. One of the most obvious is a change in the thermal regime of water bodies. How does a changing temperature regime impact flow dynamics and biogeochemical processes in streams, lakes, and reservoirs? How do thermal and hydrologic changes interact to affect freshwater ecosystems through, for example, increased eutrophication?

Management of urban and agricultural catchments for rapid water conveyance (i.e., replumbing of the water cycle) has led to increasing proportions of contaminant loads moving into and through freshwaters during peak flows. Climate change also is expected to exacerbate this phenomenon. For example, increased precipitation could increase sediment yield and contaminant runoff in agricultural dominant as well as urban- and suburban-dominant watersheds. A potential increase in contaminant loading has important consequences for downstream reservoirs, lakes, and coastal environments. How does climate change impact river flows and the flushing of constituents into down-gradient areas? Increased flooding has the potential not only to flush contaminants downstream, but also to remobilize contaminants through increased erosion. Will increased fluxes remobilize contaminants, and, if so, which contaminants are more susceptible to this remobilization?

Similarly, water extraction from surface and groundwaters has led to prolonged periods of low flows, which can aggravate contamination problems. Again, climate change is expected to exacerbate this phenomenon. In some areas there could be a decrease in precipitation leading to decreases in base flow and evapoconcentration of water, increasing salinity. In others, decreased frequency of rainfall events could introduce concentrations of non-point-source contaminants that have accumulated on the landscape over longer time periods, leading to enhanced pulses to the aquatic ecosystem. Changes in flow regimes due to changes in precipitation patterns or changes in percentages of snow versus rain might also impact water quality.

As contaminant loads are added to declining water volumes, chemical signals are amplified. Low flows in surface waters can also further exacerbate problems of low oxygen and alter the toxicity of contaminants. This concept has a variety of consequences that expand into the realm of Water and Life, because low flow shrinks habitat for aquatic species and increases the contaminant concentration and, in turn, exposure. What will be the impact of climate change induced low flows on contaminant concentrations? In the spirit of the previous chapter how does this translate to ecosystem impact?

CONCLUDING REMARKS

The committee presented research questions designed to further understand Earth's water quality in relatively pristine and impacted environments. Similar to the approach to address the challenges and opportunities outlined in Chapters 2 and 3, field studies, whenever feasible and appropriate, are important to answering the questions proposed in this chapter. Answering these questions also will require work by hydrologic scientists and engineers as well as a focused effort from those in related subdisciplines such as aquatic geochemistry and biogeochemistry. In the previous chapters the committee presented research questions probing the dynamic relationship between water and physical process and life, questions that also will require work at disciplinary interfaces. Thus, a common theme extends through the range of research questions noted in this report, that is, **the need for interdisciplinary research that takes advantage of cutting-edge technological capabilities to grapple with the complex water-related challenges of today and tomorrow.** Examples in the current context include research on groundwater age linking physical hydrologists using Darcy's Law and chemical hydrologists perfecting age-dating techniques. Or research using advances in chemical analytical techniques to help disentangle the coupled hydrological biogeochemcial processes that control the evolution of Earth's water quality profile.

Many of the research questions discussed here and in the previous chapters have relevance and applicability to the multitude of stakeholders who are concerned with water resources. For example, environmental management or stewardship requires an understanding of cause and effect as well as the ability to predict effects of different management practices on the environment. Such a predictive analysis requires not only long-term monitoring and understanding changes in water quality but also development of sophisticated models capable of representing the effects of heterogeneity, connectivity, and biogeochemical reactions on water quality at the regional scale. Thus, while the hydrologic sciences are critical to the resolution of the issues discussed in this report, it will be interdisciplinary teams of researchers, including not only physical, chemical, and biological scientists, but also social scientists, that produce useful scientific results. Ongoing consultations with those who build and maintain infrastructure are essential. To ensure that society, in additional to science, benefits from research results, interactions with policy makers and other decision makers will have to follow.

The next and final chapter presents findings for the hydrologic community to consider with respect to both advancing fundamental science and to contributing to solutions of the complex water issues of today.

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Hydrologic Sciences: A Path Forward

The previous chapters demonstrated that the opportunities in hydrologic sciences have never been greater and that the challenges that lie ahead have never been more compelling. In order to respond to these opportunities and meet the challenges of 21st-century hydrologic science, the next decade will require transformative new ways of conducting basic hydrologic research, educating the next generation of leaders, and working in new ways to ensure that the knowledge generated proves useful for solving practical problems. Many intriguing puzzles in the Earth sciences will continue to engage the community of hydrologic scientists and engineers and will attract new talent to the hydrologic sciences in the years to come. Furthermore, a changing climate, an increasingly populated planet, and competition for scarce freshwater resources demand that the hydrologic sciences deliver integrated, basic scientific knowledge in service to society. Hydrologic science extends well beyond "hydrologic science" per se, and should embrace work in other geosciences (e.g., ecology, limnology, geology, biogeochemistry), water resources, and environmental engineering. Interdisciplinary effort is a prerequisite for predicting the co-evolution of water, Earth, and life in a changing environment and for moving humanity toward a sustainable water future.

Fundamental new drivers of hydrologic sciences in the 21st century rest on the realization that (a) humans are a dominant influence on water sustainability both at the global and local scale, (b) the world is becoming exceedingly "flat,"[1] with respect to not only rapid dissemination of scientific knowledge but also learning from distant environments currently undergoing rapid change (e.g., deforestation, drought, agricultural expansion, etc.) and predicting future water scenarios in other parts of the world, and (c) the natural world is a highly nonlinear system of interacting parts at multiple scales prone to abrupt changes, tipping points, and surprises (Alley et al., 2003; Taleb, 2007) more often than previously thought possible. *What do these realizations mean for the future of hydrologic science?*

SCIENTIFIC CHALLENGES

The committee identified three major areas that define the key scientific challenges for the hydrologic sciences in the coming decade: The Water Cycle: An Agent of Change; Water and Life; and Clean Water for People and Ecosystems and provided major findings in these areas in Chapters 2, 3, and 4. Within each major area the committee enumerates some of the most challenging concepts and identifies research opportunities for attaining progress in the field; the main message of each is represented in bold, below. The challenges in these areas are the purview of the various subdisciplines within the hydrologic sciences but also related disciplines and subdisciplines. They span physical-hydrologic sciences, including physical hydrology, geomorphology, paleohydrology, and climate science; biological-hydrologic sciences, including ecohydrology, aquatic ecology, biogeochemistry, soil science, and limnology; and chemical-hydrologic sciences, including chemical hydrology, and aquatic geochemistry. These three major areas reflect both an assessment of intriguing open questions in the field and an assessment of the potential for making significant progress by virtue of previous progress coupled with new ideas, techniques, and instrumentation. Although the committee identifies the three areas separately, it is clear that there are overlaps; many of the specific research questions that will be addressed under the umbrella of these areas will bridge across the three major areas.

Water Cycle: An Agent of Change

Water is a dynamic agent whose influence is central to processes that produced the world as we know it and that will affect its evolution into the future. Many critical questions in this priority area are ripe for study both

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[1] The term "flat," coined by the author Thomas Friedman in his books *The World is Flat* (2005) and *Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America* (2008), is used to a describe new era of globalization that allows people and entities around the world to compete, connect, and collaborate.

from the standpoints of scientific curiosity and societal need. At the most fundamental level, critical gaps remain in the knowledge about hydrologic fluxes. Evaporation, transpiration, and groundwater fluxes interconnect the water, energy, and biogeochemical cycles yet adequate measurements and estimates of these fluxes are elusive, even for relatively pristine natural systems. The perturbations to the hydrologic cycle from "replumbing" through human activities add a dimension of complexity, and urgency, to this research area. **A challenge for the hydrologic community is to understand replumbing; for example, the downstream consequences of urban growth or changes in the severity, duration, and occurrence of floods and droughts as a result of climate change, and to apply this understanding to making predictions for the future. Furthering understanding of the processes that link components of the water cycle is no less important than understanding the human impacts on the water cycle.**

The processes that define water fluxes occur at many time and space scales, for example, the first drops of water that initiate streams to the complex systems of rivers that define drainage basins. Research questions are continually raised regarding the quantitative relationships among variables and across scales. **Because interactions at overlapping scales change hydrologic patterns in subtle ways, disentangling the causality of subtle shifts and regime changes in streamflow and understanding their environmental impact is a challenge.** The climate system can vary at long time scales as well as shift rapidly into new modes of behavior that are radically different from the historical experience. **Understanding the hydrologic response to abrupt climate change over short time scales and to slowly varying natural climate change is far from complete.** Exploration of how the water cycle has affected the evolution of other planets may provide important insight into Earth's water cycle and its dynamics as an agent of change and determinant of life. **The study of hydrologic processes on other planets defines the new field of "exohydrology," and research in this area is only just beginning.**

Water and Life

Water is essential for all living organisms, and, on land, the magnitude of the water supply and the timing of water delivery structures biological systems at all spatial and temporal scales. Recently ecologists, geomorphologists, climate scientists, and hydrologic scientists have found a common frontier lies at the nexus of life and water because water plays a critical role in driving the environmental patterns that exist and evolve on Earth. **The past, with radically different biota, topography, and atmospheric and ocean chemistry, presents an opportunity for hydrologists to explore how key processes in the hydrologic cycle differed, and how these processes contributed to Earth's evolution.** Hydrologic flow regimes, river channel dynamics, and aquatic ecosystems are linked, resulting in a co-evolution of rivers, wetlands, and aquatic ecosystems. **Many challenging research questions arise when exploring how topography, vegetation (and their animal ecosystems), and the hydrologic processes that connect them may co-organize over geomorphic time scales.** Subsurface ecosystems form their own environments, create and direct hydrologic pathways, release gases to the atmosphere, and control access to moisture and nutrients to aboveground ecosystems. **How subsurface biota are controlled by and yet also influence hydrologic processes is a frontier area of research.**

Earth's ecosystems are in a state of transition as a result of global warming and changing land use. **The processes that determine transitions in ecosystems are not well characterized or understood; yet the viability of ecosystems as localized communities and as part of the global co-evolution of water and life depends critically on these transitions.** Needed are theory and mechanistic field studies to guide the protection, redesign, and restoration of ecohydrologic functions on landscapes. The loss of wetlands and tributaries with high sediment-water contact is disproportionately important in driving whole watershed solute exports. However, scientists are as yet unable to understand how their continued loss (in time or in space) or altered patterns in their connectivity to downstream rivers is likely to affect patterns of solute export into the future. **An important challenge for the hydrologic and ecological communities is to understand the complex ways in which flow regimes impact critical ecological processes and the maintenance and dispersal of aquatic taxa in aquatic ecosystems. Scientists currently lack both sufficient understanding from field studies and quantitative models to make reliable predictions about desired outcomes from water management decisions in many applications.** Interdisciplinary approaches and perspectives will be needed to gain enough understanding of the interactions between water and life to predict the future states of the Earth system.

Clean Water for People and Ecosystems

Ensuring clean water for the future requires an ability to understand, predict, and manage changes in water quality. Research opportunities related to water quality stem largely from a need to know the processes that control the evolution of water quality in both relatively pristine and heavily impacted environments. Fundamental research on weathering of rocks and soils, chemical reactions in aquatic systems, and transport of materials in natural systems has yielded a solid basis for studies of water quality and will continue to build upon this base in the future. A key issue of extreme societal relevance relates to contaminants. Discharge of contaminants from a variety of activities has disturbed the planet's water chemical composition. **A research challenge exists in promoting the understanding of how**

contaminants interact with hydrologic processes and, in turn, impact stream ecosystems. The impact on water quality of growing food and providing energy for the growing global population has not been exhaustively studied, but this knowledge is critical to ensuring a sustainable future. Increasing demands for food and energy will occur against the backdrop of a changing climate, providing yet another challenge to maintaining adequate water quality for humans and ecosystems. **The hydrologic research community has an obligation to tackle the water quality issues embedded within large-scale drivers of water quality.** Geological materials are enormously complex, and many important chemical hydrologic processes are candidates for productive research exploration. **A challenge exists in developing basic hydrologic principles and tools to further understand the movement of contaminants through an irregular and interconnected world.**

The scientific areas summarized above are, in the committee's view, "the promising new opportunities to advance hydrologic sciences for better understanding of the water cycle that can be used to improve human welfare and the health of the environment" as requested in the statement of task. Some fall squarely within the purview of hydrologic science, for example, furthering the understanding of evapotranspiration and groundwater fluxes. Some require interdisciplinary efforts, such as understanding the impact of growing food on water quality. Some are "curiosity-driven," and some are "problem-driven," which the committee considers to be equally important. All reflect the complexity of the issues facing hydrologic scientists in a broad range of disciplines.

Execution of the ambitious research agenda implied by the scientific challenges above requires the ingenuity of individuals and interdisciplinary teams from numerous universities, research laboratories, and government agencies. The technological and scientific advances of today and tomorrow will continue to play a critical role. Collaborative field studies, when feasible and appropriate, are also important. In particular, ecosystem processes (especially in the case of aquatic ecosystems) can vary significantly on relatively longer time scales than do hydrologic processes, which underscores the need for collaborative fields studies in pursuit of hydrologic research.

EDUCATION ISSUES

Education of both graduate and undergraduate students in hydrologic science has gained ground in the past 20 years with the formation of new hydrologic science related programs, degrees, and other educational efforts.[2]

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[2] Recently, the National Research Council (NRC) assessed the health of doctoral institutions, programs, faculty, and students in the United States in a report titled *A Data-Based Assessment of Research-Doctorate Programs in the United States*. Since 1995, the overall number of

Along with this increase in degree-granting programs has been an evolution of the educational experience in the hydrologic sciences that is linked to the development of new capabilities and technologies (Chapter 1). Advances in technology have influenced both the skill sets imparted to students and the teaching methods employed. Students now emerge from universities technologically literate. For example, students in the hydrologic sciences may gain exposure to numerical simulations, emerging remote sensing products, new analytical chemistry methods, and many other technologies.

An emerging new forum for graduate education is "Summer Institutes," which are very popular in Europe as a means to bring together experts in the field who can teach courses that are absent from many Ph.D. programs and to expose young researchers to new ideas. In the United States, the Summer Institute on Earth-Surface Dynamics, established in 2009, focuses each year on a different but specific topic at the intersection of hydrologic and ecosystem processes in diverse environments (uplands to river deltas). Drawing on the National Center for Earth-Surface Dynamics' "approach of integrating theory, laboratory experiments, numerical modeling, and fieldwork, this two-week institute combines lectures with practical experiences in the laboratory and the field,"[3] hands-on modeling experience, as well as exposure to the broader impacts of research. Such institutes provide a "stimulating environment for learning, bonding, mentoring and life-long academic partnerships" that strengthens the research community in innovative and cost-effective ways.

Many of the challenges mentioned in previous chapters relate to transforming hydrologic research by taking advantage of new technologies, which often originate in neighbor disciplines. For example, advances in analytical chemistry led to the Synchrotron, which in turn contributed to further understanding of water-rock interactions. Educational opportunities for students in the hydrologic sciences should include exposure to new and emerging technologies, through summer programs and extended field campaigns that promote graduate student involvement. For example, students trained in the use of computational fluid dynamics simulators or analytical instruments will gain a skill set that crosses many disciplinary boundaries and will establish linkages with practitioners in other disciplines.

Fostering interdisciplinary graduate education can be challenging because often academic departments are organized along traditional disciplinary lines. However, successful models exist that demonstrate how to

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Ph.D.'s produced by doctoral programs in the United States has increased by 11 percent including an increasing number of international students pursuing doctoral programs in the United States. The number of students enrolled in physical and mathematical science programs, which includes hydrologic science programs, has increased by 9 percent (NRC, 2010a).

[3] See http://www.nced.umn.edu/content/summer-institute-earth-surface-dynamics.

implement an interdisciplinary educational experience that complements programs of single-discipline academic departments. Needed in the future are broader graduate level educational experiences that cross disciplinary boundaries in pursuit of the opportunities presented in this report.

Opportunities also exist at the undergraduate level. Hydrologic sciences can respond to a young generation interested in solving sustainability problems by introducing innovative education experiences early in educational programs, for example, incorporating service into a degree program. Service could include water-related aid work in developing countries, for example, a "Water Corps." Student organizations in other disciplines could serve as models for channeling student enthusiasm into experiences that are educational and contribute to the broader community. Examples include Engineers Without Borders, informal geology or environmental clubs at many universities, and student chapters of professional societies such as the American Meteorological Society, the American Water Resources Association, and the American Institute of Hydrology, all of which have records of achievement in community outreach.

All of these service-minded activities are in the spirit of "hydrophilanthropy." Furthermore, a short period of practical experience as part of hydrologic science undergraduate and entry-graduate education could attract motivated and focused students to the discipline and provide them with an understanding of the social and technical complexities of water problems. Such novel programs might be an effective for recruiting a new generation of researchers and providing them with a holistic and motivating perspective. Indeed, the University of New Mexico introduced hydrophilanthropy to students by offering a series of trips to Honduras, where participants helped villages build rural water systems. These trips attracted dedicated students who sought the program out of a desire to work in developing countries. (For additional information about hydrophilanthropy, see the *Journal of Contemporary Water Research and Education*, Issue 145, August, 2010.)

> Hydrophilanthropy is a term used to describe altruistic efforts of colleagues to provide sustainable, clean water for people and ecosystems worldwide.
>
> *David K. Kreamer (2010)*

The opportunities and challenges presented in this report can be met by educating scientists and engineers in both traditional and nontraditional ways. The committee notes the importance of developing T-graduates[4] who can perform antedisciplinary science[5] and other graduates who function well in interdisciplinary teams. **To tackle the complex issues outlined in the report, those who guide young hydrologic scientists and engineers should consider how to best prepare them for a scientific arena that differs from the norm.** In this regard, tailored educational experiences that develop intellectual breadth and enrich communication skills will supplement traditional activities that train students to be independent researchers.

IMPORTANCE OF VARIOUS MODALITIES OF RESEARCH SUPPORT

This report is a result of a study funded by the National Science Foundation (NSF). The broad charge to identify promising new research opportunities is not specific to NSF. In other respects, the committee interpreted its charge to comment on current research modalities,[6] education opportunities, and strengthening observational systems, data management, modeling capacity, and collaborations, including interfaces with mission agencies, to be a request from NSF for specific advice. Much of this advice may apply in varying degrees to other agencies, but the committee uses examples from NSF programs in the following discussion.

A primary aim of NSF programs is to conduct discovery-driven research to create basic knowledge in service to society. The broad sweep of the entire report is relevant to this aim with respect to the hydrologic sciences. Other agencies and organizations are involved in hydrologic science research and have interests in various modalities of research support. In this light, the critical elements of the committee's advice relate to (1) investing in hydrologic science by collaborating across programs, divisions, and directorates and by establishing a balanced portfolio of single-principal investigator (PI), multi-PI, and community-driven interdisciplinary research and education to advance the scientific frontier and to develop "the T graduate" capable of both disciplinary depth and intellectual breadth; (2) fostering collaboration among agencies and nations in hydrologic science

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[4] A "T-shaped" person is a revolutionary-type who drives innovation. Often used to describe those in the workforce or in job recruitment, they have both depth and breadth of knowledge and interest. They are able to work in an interdisciplinary fashion and see how ideas, sectors, disciplines, and people intersect and connect. For more information see http://www.kauffman.org/advancing-innovation/innovation-that-matters.aspx.

[5] Eddy defines antedisciplinary science as the science that precedes the organization of new disciplines.

[6] The committee interprets the term "modalities" in the statement of task as referring to capabilities within the NSF and other federal agencies used to advance hydrologic research including contracts and research grants, instrumentation and facilities, and so forth.

research, facilities, data and model sharing, as well as educational experiences; (3) creating innovative new ways of communicating research results to policy and decision makers; and (4) creating new modes of interaction among physical and socioeconomic sciences relevant to water sustainability.

Taking Stock and Looking Ahead

To successfully solve today's complex water problems within the three major areas (Water Cycle: An Agent of Change, Water and Life, and Clean Water for the Future), scientists, engineers, and water managers need both a disciplinary depth and intellectual breadth to bridge disciplines and to effectively communicate science to policy makers. As technology to probe Earth's mysteries advances, computer models become more sophisticated, research relies on ever more extensive data for modeling and analysis, and no single discipline provides the entire knowledge base, building mechanisms to share knowledge, equipment, models, data, and science requires a fostering platform and relevant resources. In light of these needs, entities that support hydrologic science research could include investing in single PI research, larger interdisciplinary groups, and community capacity building in their future approaches. Efforts to work in harmony rather than in competition foster a culture of sharing and growth within an environment of curiosity-driven research for the benefit of society. The necessary research would be performed by not only interdisciplinary individuals who may provide truly exciting breakthroughs (e.g., Eddy, 2005) through the standard research grant mode, but also individuals who do their most creative work as partners in interdisciplinary research funded by larger research initiatives. Consequently, NSF would be well positioned to meet future programs needs by maintaining an appropriate balance among its funding modalities.

Standard Research Grants

Research grants or contracts to individual PIs come from a variety of federal, state, and local agencies and from private sources as well. An important part of this broad package is the NSF's Hydrologic Sciences (HS) program in the Earth Sciences Division (EAR) of the Geosciences Directorate (GEO). Sixty-three percent of total federal funding to universities for basic geosciences research originates from NSF's GEO (NSF, 2010). Support for research performed by individual investigators and small groups of researchers is awarded by core programs through grants and continues to be the backbone of EAR efforts. Approximately 90 percent of the HS program budget supports this program element.

The extent and breadth of the hydrologic science research that has been initiated and expanded since the launch of the HS program 20 years ago confirms the community's valuation of curiosity-driven research, articulated in the "Blue Book" (NRC, 1991), whose authors recommended creation of the HS program. One measure of the success of the HS program is the high proposal submission rate, which reflects an expanding and vibrant talent pool ready to address the challenges of the future (Figure 5-1). At the same time, the low funding success rate of proposals submitted through the standard grants competition (declining from 30 percent in 1999 to less than 20 percent in 2007, Figure 5-2) indicates the limited capacity of the program to support the research proposed by the hydrologic sciences community. **Hydrologic science is well served by the HS program's support of standard grants. This core research capability will continue to be important as NSF addresses the opportunities and challenges described in this report. As other agencies and organizations approach the challenges described in this report, their support of individual PIs also will be important.**

An opportunity exists to capitalize on the success of the PI driven program element through collaborative work by groups of PIs. One example is campaigns of field expeditions to collect data from multiple sources over extended time periods and over fairly large areas. The benefit of this type of activity has been demonstrated by other communities, such as in the FIFE

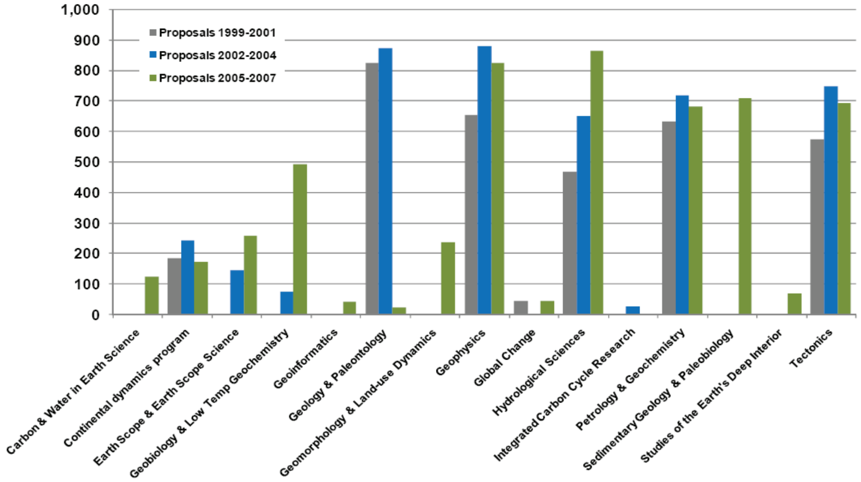

FIGURE 5-1 Number of proposals submitted to the National Science Foundation for selected topics illustrating an increase in the number of proposals on hydrologic sciences. SOURCE: Modified, with permission, from American Geological Institute (2009). © 2009 by the American Geological Institute.

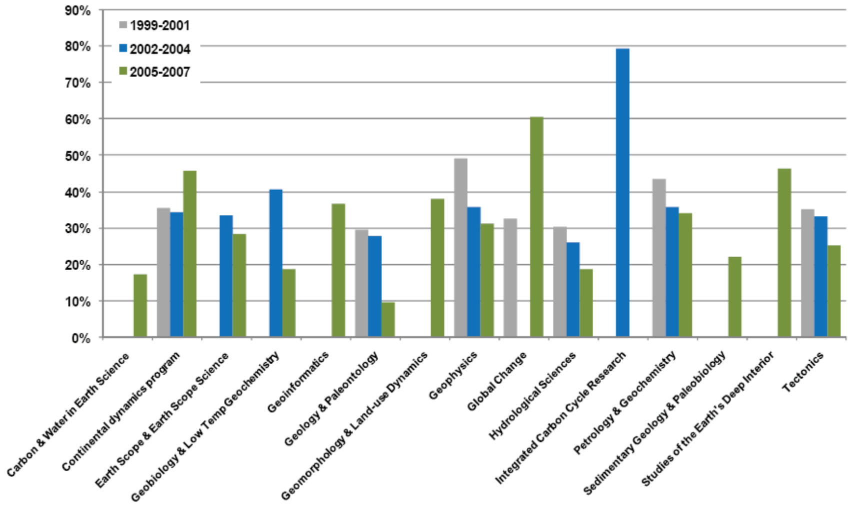

FIGURE 5-2 Funding proposal rate at the National Science Foundation for selected topics illustrating a decline in the funded proposals for hydrologic sciences from 1999 to 2007. SOURCE: Modified, with permission, from American Geological Institute (2009). © 2009 by the American Geological Institute.

experiment of the 1980s and 1990s[7] to elucidate land-atmosphere exchange of carbon and water at multiple scales. Other types of collaborative efforts could include development of community models as has been successfully done by the atmospheric science community,[8] and sponsorship of synthesis activities as has been done by the ecology community (National Center for

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[7] The FIFE projects or experiments of the late 1980s and early 1990s were central to NASA's International Satellite Land Surface Climatology Program. The first experiment was conducted on the Konza Prairie in Kansas, a 15 × 15 km area of grassland, and a follow-up experiment at the same location a few years later. The objective of the FIFE experiment was to "understand the biophysical processes controlling the fluxes of exchanges of radiation, moisture, and carbon dioxide between the land surface and the atmosphere; develop and test remote-sensing methodologies for observing these processes at a pixel level; and understand how to scale the pixel-level information to regional scales commensurate with modeling of global processes." This was achieved through coordinated data acquisition (satellite, airborne, and ground measurements) and a scaling-up analysis by roughly 100 science investigators and support staff. SOURCE: http://daac.ornl.gov/FIFE/FIFE_About.html. For more information see http://daac.ornl.gov/FIFE/fife_campaign.html.

[8] An activity of the National Center for Atmospheric Research located in Boulder, Colorado. For more information see http://ncar.ucar.edu/community-resources/models.

Ecological Analysis and Synthesis).[9] The committee encourages the research community to explore such collaborative efforts. **Collaborative, community building efforts will continue to be relevant for the multiple agencies and organizations that support hydrologic science, including NSF in general and the HS program in particular, in responding effectively to many of the opportunities and challenges presented in this report.**

Facilitation of Community Engagement

Following extensive discussion and recognition by the water science community of the need to engage in thinking about future challenges for research and education in the field, NSF's HS program is supporting facilitation of community growth via the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). Founded in 2001, CUAHSI is an organization of 126 universities, affiliate member universities, and a smaller number of international affiliate members, and its mission is to enable "the university water science community to advance understanding of the central role of water to life, Earth, and society" (CUAHSI , 2010).

Many researchers from the community believe that CUAHSI has fostered a spirit of cooperation by determining how groups can better work together to enhance the field in terms of knowledge generation and sharing. In particular, smaller universities with limited resources now have opportunities that were previously unavailable to them. The committee anticipates that the community will continue to value and to derive benefit from efforts to facilitate collaborative research and the NSF portfolio will continue to include program elements that support this kind of community effort. Having a "community voice" will cultivate exchanges with similar, international, community-wide entities and thus advance efforts in building shared research infrastructures (physical and computational) that will enable and facilitate a global water science research and education perspective.

Instruments and Facilities

A critical avenue for research support in the hydrologic sciences is facilities. Several federal agencies and some private foundations provide support for facilities. One major source of such funds for universities is the NSF. Currently, EAR devotes about 35 percent of its budget to Instrumentation

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[9] The National Center for Ecological Analysis and Synthesis, located in Santa Barbara, California, supports cross-disciplinary research in ecology and allied fields. For more information see http://www.nceas.ucsb.edu/.

and Facilities and Major Research Initiatives.[10] An example of a facility that directly impacts hydrologic science is the NSF-supported research center, the National Center for Airborne Laser Mapping, to enable the use of airborne laser mapping technology in the scientific community.[11] EAR also now directly supports hydrologic instrumentation user facilities in distributed fiber-optic sensing[12] and mobile radar facilities for hydrologic observatories. Development of community-based NSF instrumentation facilities represents a relatively new mode of operation for the hydrologic sciences. These facilities are designed to provide major, state-of-the-art equipment to researchers in hydrologic and related sciences and have already proven very successful in training scientists and in deploying instrumentation.

The "sensor revolution" mentioned in Chapter 1 represents a fundamental advance and is fueled by advances from inside and outside the field of hydrologic science. Hydrologic science will be continuously challenged to search for and test new and emerging technologies. Fortunately, the availability of novel and emerging instrumentation continues to increase, through the expansion of NSF's community instrumentation centers, the development of instrument sharing through the CUAHSI Hydrologic Measurement Facility, as well as collaborative efforts with other Earth science disciplines already heavily invested in community instrumentation such as UNAVCO[13] and PASSCAL.[14] The development of Critical Zone Observatories (CZOs) also can continue to serve as a driver to test and incorporate sensors that provide highly granular data. Similarly, the availability of new instruments supported through programs of, for example, the Department of Energy and NASA, will be important.

The sensor revolution brings with it several significant but exciting challenges. Incorporating sensor data with high resolution into models that operate at coarser spatial resolutions and using these data effectively will be a theoretical and computational upscaling challenge. If the sensor

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[10] The budget for NSF's EAR is available online at http://www.nsf.gov/about/budget/fy2011/pdf/08-GEO_fy2011.pdf.

[11] See http://www.ncalm.cive.uh.edu/index.html.

[12] The Center for Transformative Environmental Monitoring Programs (CTEMPs) provides "field-deployable high-precision fiber optic temperature measurement systems and wireless self-organizing multi-parameter sensor stations" to the Earth science community in the interest of discovery and education. For more information see www.ctemps.org.

[13] UNAVCO is a nonprofit, university-governed consortium that facilitates geoscience research and education by providing support to PIs engaged in NSF-supported research. Most of the organization's activities are centered in the UNAVCO facility in Boulder, Colorado. For more information see http://www.unavco.org/aboutus/aboutus.html.

[14] The Incorporated Research Institutions for Seismology (IRIS) Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrumentation Center at New Mexico Tech is a facility dedicated to research into Earth's geologic structure and processes. For more information see http://www.iris.edu/hq/programs/passcal.

revolution is to be sustained, the next generation of hydrologic scientists will need to be able to communicate and work in a wider range of science and engineering, with specific focus on physics, electrical engineering, and computer science. Finally, the management and dissemination of hydrologic data sets much larger than those of the past will require the field to learn and use information technology from other data-intensive disciplines.

Support for facilities and instrumentation will continue to be an important resource for the hydrologic sciences community now and in the future. The sensor revolution implies that new development of measurement systems and instruments will be rapid and will need to be disseminated to the hydrologic sciences community. **Support for instrumentation and facilities by the various entities that make such support available, including the EAR Instrumentation and Facilities (IF) program, will continue to be important to encourage novel instrument development for the wide range of measurement facilities, sensors, sensing platforms, and sensing support facilities that are critical to the advancement of hydrologic sciences within the broader geosciences perspective.**

Broader NSF Research Initiatives

NSF has a number of program elements that promote interdisciplinary research in hydrologic sciences and fall outside of the standard grants process. Two examples are provided here to highlight the importance of such elements to meeting some of the research challenges presented in the previous chapters.

In recognition of the need for sustainability to address a host of critical problems facing the nation, NSF started a foundation-wide initiative on Science, Engineering, and Education for Sustainability (SEES). Much of the research within this general initiative will involve hydrologic science. Other cross foundation initiatives, such as one on Sustainable Energy Pathways and Critical Zone Observatories have clear links with hydrologic science and can take on some of the critical research opportunities outlined in this report.

NSF also provides support by its funding of Science and Technology Centers (STCs), through the STC program of its Office of Integrative Activities. This program provides long-term, large-scale awards for innovative, complex research and education projects within any discipline or at the interface of any discipline(s) that NSF supports by a “center mode,” where awards initiate and correspond to the life of a Science and Technology

Center.[15] NSF has supported two STCs with strong links to hydrologic sciences over the past decade—the National Center for Earth Surface Dynamics and the Center for Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA). A recent assessment of STCs indicates that they are quite important in shaping how faculty and students undertake research on complex and often very interdisciplinary topics:

> Perhaps the most striking aspect of faculty responses to these questions is the extent to which faculty in both survey cohorts indicate that the research that they engage in as members of an STC involve higher degrees of risk-taking and have greater potential to be transformative than the research they engage in outside of the STC (Chubin et al., 2010).

Engineering Research Centers (ERCs)[16] are another group of multidisciplinary centers sponsored by NSF, including a new center (as of 2011) on developing sustainable ways to manage urban water. Although its emphasis is on engineering, the Urban Water ERC will address topics related to Earth and hydrologic science sciences. Because of the growing need for interdisciplinary research, the committee anticipates that efforts such as the Urban Water ERC will continue to be important to hydrologic sciences. The committee encourages the hydrologic community to vigorously pursue such opportunities, which add both intellect and resources to the core HS program.

Educational Program Elements

Along with all other areas of science, hydrologic science has benefited from many programs that support graduate students, the most obvious being support of graduate research assistantships on competitively funded NSF grants (see earlier section, Standard Research Grants). The NSF Graduate Research Fellowship Program (GRFP) is designed to support basic research and graduate degrees in all program areas that NSF funds. The program was founded in 1951 and is the oldest fellowship program in the United States, supporting graduate students in various science, technology, engineering, and mathematics fields. The fellowship is available and routinely awarded to students in the geosciences, including young hydrologic scientists. The fellowship has been offered to several graduate students citing "Geosciences-Hydrologic Sciences" as their primary field of study in recent years (Table 5-1). However, the number of fellowships for such

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[15] The STCs use the "center mode" to support investigations, with five new centers started and the "graduation" of the five centers (initiated in 2000) in the fall of 2010. As of the spring of 2011, there were 17 current awards. For more information see http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5541.

[16] See http://www.erc-assoc.org/.

TABLE 5-1 Number of Graduate Fellowships Offered over the Past 6 Years Through NSF's Graduate Research Fellowship Program (GRFP) to Students Who Cited Hydrologic Sciences as Their Primary Field of Study

Year	NSF GRFP Offered in Hydrologic Sciences[a]	Total NSF GRFP Offered
2005	2	1024
2006	4	909
2007	0	920
2008	1	913
2009	6	1248
2010	5	2051
2011	5	2000

[a] Currently, the GRFP offers more than 150 choices for primary field of study, 17 of which are in geosciences. These choices include hydrologic science and fields closely related to hydrologic science such as geochemistry, geology, and paleoclimate.
SOURCE: NSF Fastlane database. Available online at https://www.fastlane.nsf.gov/grfp/AwardeeList.do?method=loadAwardeeList [accessed August 6, 2012].

study did not increase appreciably between 2009 and 2011 when the total number of graduate fellowships awarded by NSF nearly doubled. Graduate fellowships also are part of other programs, including the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) fellowship,[17] the Department of Defense fellowship (the National Defense Science and Engineering Graduate Fellowship),[18] the National Oceanic and Atmospheric Administration's graduate research fellowships,[19] as well as fellowships from foundations.

Looking ahead, the committee envisions that the relevant agencies and organizations will appropriately extend support for interdisciplinary graduate education. As an example, the CUAHSI Pathfinder Graduate Student Fellowships to Support Multi-site Research in Hydrology provides travel support for graduate students to collaborate with researchers beyond their own field site. Young hydrologic scientists and engineers also can participate in the Integrative Graduate Education and Research Traineeship (IGERT) program, an NSF-wide endeavor to foster collaborative research across traditional boundaries through new models for graduate training. Active IGERT programs are classified by "themes" reflecting the interdis-

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[17] See http://epa.gov/ncer/.

[18] See http://ndseg.asee.org/.

[19] See http://www.oesd.noaa.gov/fellowships_opps.html.

ciplinary nature of each; 14 current IGERTs list water as one dimension of their theme.[20]

Undergraduate students also are demanding greater access to interdisciplinary research opportunities. Within NSF, Research Experiences for Undergraduates (REU) programs are an opportunity to promote cross-disciplinary research experiences, both domestically and internationally.[21] REU programs provide a means to engage researchers from a variety of disciplines and therefore can promote cross-disciplinary interaction among mentoring scientists as well as students.

Increasing the participation of underrepresented groups in the geosciences is an important goal of the NSF GEO. The hydrologic sciences can contribute substantially to this effort by not only increasing the representation of underrepresented groups in the field, but also providing leadership to build scientific capacity within underrepresented communities. An example of this type of activity is the development of the first Hydrology and Water Resources degree program in a tribal college, the Salish Kootenai College in Montana, which will foster the development of local capacity for managing tribal lands. This program is unique to Tribal Colleges and can provide impetus for increasing the exceptionally low numbers of Native American graduates in the geosciences in general and in hydrologic science in particular.

NSF has well-established programs that can support education modalities mentioned above. **Continued NSF support of various educational modalities will enable beneficiaries to fulfill the research goals described in this report.**

Collaboration with Other Federal Agencies and with International Organizations

Numerous U.S. federal agencies have varying degrees of responsibility in water science or water management, including NSF (Figure 5-3). These agencies fund research related to their missions, although only a fraction would be considered to be in "hydrologic sciences." The nature of many of the challenges facing the hydrologic sciences is such that coordination and collaboration between research supported by NSF research supported by these other agencies will be essential. A few examples of how such efforts can be mutually beneficial are noted below.

NOAA's Community Hydrologic Prediction System[22] is an example where NSF research can be leveraged to improve a critical forecast service

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[20] See http://www.nsf.gov/crssprgm/igert/intro.jsp.

[21] See http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517&org=NSF.

[22] See http://www.nws.noaa.gov/oh/hrl/chps/.

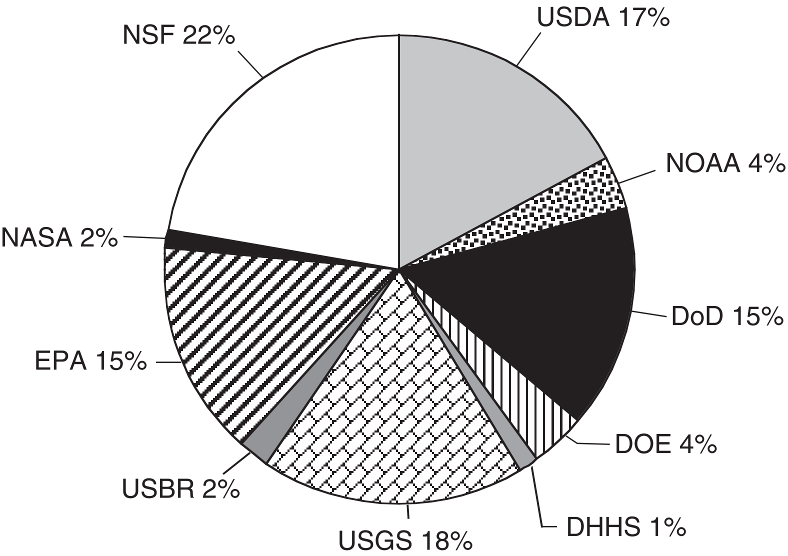

FIGURE 5-3 Funding for U.S. research in water resources in 2000. The data in the figure are from a survey of federal agencies in which data collection activities (such as satellites and their instruments) were specifically excluded. SOURCE: NRC, 2004.

and deliver the basic science required for improving hydrologic predictions (NRC, 2010b). Key remote sensing products provided by NASA will drive many of the advances in land surface-atmosphere hydrologic science that are described in Chapter 2, which necessitates coordination and collaboration with NASA[23] supported researchers. Synthesis of existing knowledge across many disciplines is another challenge that stems from the broad interdisciplinary nature of some of the research questions posed in this report. The NSF may be able to collaborate with the U.S. Geological Survey's recently established Powell Center.[24] The recent collaboration with U.S. Department of Agriculture on the Water, Sustainability, and Climate initiative is another example of a leveraging opportunity that will benefit both agencies. The committee views such extended program elements to have been very successful to date, and likely to be even more so in the near future. As other federal agencies continue to develop strong research programs, national centers, and collaborative projects in water and water resources, such extended program elements will continue to be successful. **Expansion**

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[23] See http://neptune.gsfc.nasa.gov/hsb/.

[24] See http://www.fort.usgs.gov/news/news_story.asp?WebID=100727.

of cross-agency programs and exploration of novel mechanisms of cross-agency partnerships, including opportunities to make use of observational programs and facilities, are likely prerequisites for effective response to the research goals suggested in this report.

The hydrologic sciences community has always embraced an international perspective in its research but primarily in an informal manner. Formal ways of fostering international collaboration within NSF's portfolio of activities in environmental sciences and engineering will be needed in the future. The U.S. CZOs are collaborating with a parallel program in the European Union (Soil Transformations in European Catchments or SoilTrEC[25]) to extend data and infrastructure availability broadly across nations. This effort is part of the EU-U.S. collaboration on "common data policies and standards relevant to global research infrastructures in the environment field" and the "e-infrastructures" program that are beginning to develop a common framework for sharing data, science, and models in environmental sciences.

The hydrologic science community can achieve substantial benefits by promoting common standards for data sets and their compatibility with hydrologic modeling platforms. For example, the climate modeling community through the Coupled Model Intercomparison Program (CMIP)[26] has established standards for data structure, formatting and metadata, primarily by requiring that all model output submitted to the CMIP archive use NetCDF formatting following climate and forecasting standards for metadata. An outcome of this common structure has been an explosion in the number of multimodel analyses applied to a wide variety of simulated fields from global climate models. In addition, the common structure has encouraged software development and sharing, because scientists do not have to rewrite software for each new model or field analyzed. The software sharing has promoted more sophisticated analyses and the movement of multimodel archives into a distributed computing ("cloud") environment. Such standards are starting to spread through the climate modeling community to other types of climate models, such as regional models, and to observational data sets. The hydrologic community could achieve comparable benefits through standardization of model output and observational records.

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[25] See http://www.soiltrec.eu/.

[26] See http://cmip-pcmdi.llnl.gov/.

TRANSLATIONAL HYDROLOGIC SCIENCE: THE KEY TO SUCCESS THROUGH BROADER IMPACT

The lack of access to safe drinking water for nearly 3 billion people on Earth is an urgent humanitarian crisis. Reducing this number is a primary goal of the United Nations Millennium Development Goals on Environmental Sustainability.[27] Human consumption now constitutes a significant fraction of the net biological productivity of the planet, and anthropogenic impacts on freshwater quality and availability are notable in most places in the world, especially in densely populated developing countries. Furthermore, the United Nations Millennium Development Goals to End Poverty and Hunger propose a large increase in food production, with only a limited acknowledgment that this will require dramatic changes in the way freshwater is currently used. Solutions to global water resources problems are only achievable through action at local and regional levels. The research needed to inform sound water management and policy decisions cannot be done without engagement of stakeholders throughout the entire length of the project. That is, by engaging in joint discussions, scientists, engineers, and decision makers will gain a perspective on what judgments must be made and what potential impacts may occur. The general approach has been called the analytic-deliberative process (Box 5-1).

The research proposed in this report focuses on the physical, chemical, and biological processes that operate within a suite of global cycles and that affect the supply and quality of the planet's water resources. However, improved knowledge of these processes does not necessarily translate into improved management. In order to better connect science and decision making, sustained interactions are needed among scientists, engineers, water managers, and decision makers. Science conducted in this fashion is called translational science, and it has most notably been applied to medical science. In this application, "translational" refers to both the communication of science to decision makers and the communication of users' needs to scientists and engineers so they can better understand their research. These groups can work together to determine what scientific research is needed and how the results from the work decision making.

Water challenges include insufficient and degraded water supplies for both humans and ecosystems. Hydrologic science, broadly defined, is critical to meeting these challenges. However, solutions require translational hydrologic research—"translational hydrologic science"—that considers social, institutional, economic, legal, and political constraints. This clearly

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[27] Goal 7 of the United Nation's Millennium Goals is to "Ensure Environmental Stability." Within this goal are several targets, one of which is to "halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation." For more information see http://www.un.org/millenniumgoals/.

BOX 5-1
The Analytic-Deliberative Process

The analytic-deliberative process integrates scientific analysis with deliberation to guide situations where judgment by decision makers is necessary. Within this framework, science illuminates how policy options will impact, for example, water resources as well as characterizing and reducing uncertainties and disagreements by providing new scientific information. In the process, the relationship between scientists and decision makers relies on shared responsibility for making judgments that are guided by broadly based deliberation involving stakeholders rather than scientific analysis alone to inform policy.

SOURCE: Dietz and Stern (1998).

necessitates broad, interdisciplinary projects that are place based and that include physical, chemical, biological, and social scientists as well as local stakeholders. Research agendas are collaboratively produced by scientists, engineers, decision makers, and stakeholders. Engagements are interactive (multiway), sustained, with feedbacks and iterations, and involving a time commitment from all parties. An evaluation process, independent of the parties involved, is critical for successfully proposing, evaluating, and executing translational research. Was the science ultimately useful in addressing the stakeholder needs or concerns?

How the SAHRA participated in translational research in the San Pedro Basin, which straddles southeastern Arizona and northern Mexico, provides an example of such research through NSF STCs (Box 5-2). Other agencies have recognized the need for translational science as well. NOAA has funded Regional Sciences and Assessments programs, some of which have been in existence for more than a decade, demonstrating the challenges and successes that come from problem-driven science. These regional programs focus on climate information and products that would benefit management and decision making. Research has addressed climate and health issues (e.g., West Nile disease), long-term water resource planning using paleohydrologic data, drought planning and monitoring in tribal lands, and seasonal forecasts for agriculture.

The NSF does not have a long record of supporting research that truly meets the goals of translational hydrologic science. The broad initiative on Water Sustainability and Climate (WSC) appears to be one activity where innovative basic research within the analytic-deliberative framework might break with this tradition. In undertaking such research efforts it is acknowl-

BOX 5-2

Integration of Science with Elected Officials and Resource Managers in the San Pedro: Time, Trust, and Lessons Learned

NSF sponsored research in the Upper San Pedro Basin (USPB) provides an example of long-term integration of science with policy and decision making focused on water sustainability. This semi-arid basin originates in northern Sonora, Mexico, and flows north into southeastern Arizona. It is one of the most ecologically diverse areas in the Western Hemisphere and contains some of the last perennial streams in the region. In 1988, Congress established the San Pedro Riparian National Conservation Area (SPRNCA), the first of its kind in the nation, to protect this area's riparian resources. The aquifer that sustains perennial flows in the San Pedro is virtually the sole source of water for two major, and growing, economic drivers in the basin—the Cananea mine in Mexico, which produces 2 to 3 percent of the world's copper when in operation, and the Fort Huachuca Army base, the largest employer in southern Arizona and integral to global military communications. This aquifer has experienced severe drawdown and continues to be pumped at excessive rates.

In 1998, the Upper San Pedro Partnership (USPP),[a] consisting of 21 agencies and organizations was formed to facilitate and implement sound water management and conservation strategies in the Sierra Vista subwatershed of the USPB. The Partnership's mission is to work together to achieve sustainable yield of the regional aquifer to preserve the SPRNCA and ensure the long-term viability of Fort Huachuca. The USPP consists of multiple stakeholders including research scientists from the U.S. Department of Agriculture's Agricultural Research Service and the U.S. Geological Survey. These scientists have met with resource managers and election officials roughly three times per month within various committees since USPP's inception. This extended interaction has laid the groundwork for a strong foundation of trust between scientists and decision makers and has paved

edged that their purpose is to inform policy and provide a scientific basis upon which policies themselves can be fashioned. The actual making of public policy needs to be in the hands of the policy makers. The proposition that underlies the need for scientific input to policy-making processes is that policies that are well informed by science are more effective and useful than those that have not considered, simply ignored, or rejected science. **The committee encourages agencies and organizations to support an interpretation of solicitations on interdisciplinary hydrologic science that allows fair consideration of the new research directions in translational hydrologic science that are needed to solve societal problems.**

Underpinning success in translational hydrologic science is successful communication between involved groups, which includes interactions between scientists and engineers from different disciplines; scientists, engithe way for interdisciplinary research conducted by the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA), the first NSF Science and Technology Center that focused on water resources.[b]

As a key objective, SAHRA, in concert with the USPP, identified stakeholder-relevant questions and initiated the design of research and monitoring to address these questions. This research produced a number of key science products ranging from quantification "of the temporal and spatial water needs of riparian vegetation in the SPRNCA" to "an assessment of how groundwater pumping from different zones within the basin affects the river" (Saliba and Jacobs, 2008). The collaborative science also contributed directly to addressing key partnership goals (e.g., a two-thirds reduction in the annual pumping deficit) and was instrumental in new policy initiatives (e.g., local zoning laws to encourage growth and pumping away from the river as well as two new landmark state water statutes).

This research collaboration offered several clear lessons. Ongoing and regular face-to-face communications between senior scientists and decision makers enables the two groups to learn each other's "language," builds trust, and fosters mutual learning. Scientists learn the social, economic, and political agenda and constraints. Decision makers gain a better understanding of the natural system as well as an appreciation of the uncertainties. Such collaboration is essential to adaptive management, which enables decision makers to rapidly implement low-risk management strategies while additional science and monitoring are conducted for high-risk projects. Active engagement of stakeholders and the general public from the beginning of the project greatly improves the likelihood that recommendations will be implemented (Richter, 2010).

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[a] See http://www.usppartnership.com/.

[b] See http://www.sahra.arizona.edu/.

neers, and decision makers; and scientists, engineers, and the informed public. Yet communication can often be challenging because of, for example, the lack of a common vocabulary or a common understanding of terms (NRC, 2011). Given the interdisciplinary perspective needed to address future challenges in water sciences, the importance of strong communication skills will only increase. **The educational experiences for young hydrologic scientists should include experiences that enhance communication skills.**

CONCLUDING REMARKS

This report challenges scholars in the hydrologic sciences to engage in research that is both relevant and exciting, continues to promote education to ensure a new generation of hydrologic scientists and engineers equipped to face future water resource challenges is born, and continues the high standard of quality research supported by NSF. This includes a call for disciplinary and interdisciplinary research to shed light on the wonderfully complex scientific puzzles that present themselves to hydrologic scientists and engineers as well as research to meet the increasingly complex water-related challenges facing the United States and the globe. Some broad approaches will facilitate the hydrologic community's ability to answer this challenge:

- Interdisciplinarity: There is a need for interdisciplinary hydrologic research that takes advantage of cutting-edge technologies to grapple with the complex water-related challenges of today and tomorrow. As technology to probe Earth's mysteries advances, computer models become more and more sophisticated, research relies on ever more extensive data for modeling and analysis, and no single discipline provides the entire knowledge base; building mechanisms to share knowledge, equipment, models, data, and science requires a fostering platform and relevant resources.
- Range of Modalities: A range of modalities plays a critical role in hydrologic sciences that is key to tackling the challenges and opportunities in this report.
- Education: To successfully solve today's complex water problems, scientists, engineers, and water managers need disciplinary depth and intellectual breadth to bridge disciplines and the ability to effectively communicate science to policy makers.
- Translational Science: Multiway interactions among scientists, engineers, water managers, and decision makers (termed "translational hydrologic science") are needed to more closely connect science and decision making in order to address increasingly urgent water policy issues.

All of the research challenges described in this report invite a large number of focused questions within the disciplines represented by the hydrologic sciences. Equally important, the research challenges clearly point to the need for cross-disciplinary efforts to augment and supplement the more traditional activities within disciplines. Consequently, hydrologic science should partner with associated disciplines in ever more varied ways. Success in preparing proposals, evaluating proposals, and conducting the research effectively will require creativity within the research community and within the federal agencies that support research in the hydrologic sciences.

This committee was asked specifically to comment on challenges and opportunities within hydrologic science and associated Earth and biological sciences. Nevertheless, the committee is compelled to point out that, while such research is definitely necessary, it is not sufficient. As water problems become more complex and as global water scarcity continues to manifest itself in different ways, the need for science-based public policies to guide water management will continue to intensify, presenting challenges that have not heretofore been addressed in any consistent way. The results of hydrologic studies are frequently unavailable to policy makers who may be unfamiliar with the terminology and have no technical training that would allow them to understand and interpret the results. Sometimes it is unclear whether and how the implications of findings in the hydrologic sciences will have relevance for public policy. The water management challenges of the future will be even more difficult to address if the significant findings in hydrologic sciences are left to find their way into policy-making processes by serendipity.

The challenges of the future, therefore, will require more systematic attention to the importance of hydrologic sciences in the public policy process. In turn, researchers in the hydrologic sciences will be required to collaborate and communicate with colleagues in the social sciences, including economics, political science, psychology and sociology to a far greater extent than has been the case in the past. Collaborative work with the social sciences will be helpful in identifying appropriate specific contexts for hydrologic sciences in the policy-making process, interpreting hydrologic sciences in terms of both economic and social implications and, ultimately, in identifying how hydrologic sciences can contribute as fully as possible to the advancement of human and societal well-being.

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Appendix A

Contributors to the Report: *Challenges and Opportunities in the Hydrologic Sciences*

Numerous persons contributed to the development of this report. Some provided material and talks at the committee's request, some provided unsolicited material, and some provided advice for the committee to consider. The committee would like to thank all of these persons for their interest in and support of this effort.

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Appendix B

Biographical Information: Committee on Challenges and Opportunities in the Hydrologic Sciences

George M. Hornberger, *Chair*, NAE, is Distinguished University Professor at Vanderbilt University, where he is the Director of the Vanderbilt Institute for Energy and the Environment. He has a shared appointment as the Craig E. Philip Professor of Engineering and as professor of earth and environmental sciences. He previously was a professor at the University of Virginia for many years, where he held the Ernest H. Ern Chair of Environmental Sciences. His research is aimed at understanding complex water-energy-climate interrelationships and at how hydrologic processes affect the transport of dissolved and suspended constituents through catchments and aquifers. Dr. Hornberger is a fellow of the American Geophysical Union (AGU), of the Geological Society of America, and the Association for Women in Science. He has served on numerous boards and committees of the National Academies, including as chair of the Commission on Geosciences, Environment, and Resources (1996-2000) and the Board on Earth Sciences and Resources (2003-2009). He currently is a member of the Water Science and Technology Board (WSTB). Dr. Hornberger received his B.S. and M.S. from Drexel University and his Ph.D. in hydrology from Stanford University.

Emily S. Bernhardt is an associate professor at Duke University in the Department of Biology and the Nicholas School of the Environment. Dr. Bernhardt holds a B.S. in biology from the University of North Carolina (UNC), Chapel Hill, and a Ph.D. in ecology and evolutionary biology from Cornell University. A biogeochemist, her research program is fundamentally concerned with understanding how nutrient cycles are changing as a result of human-accelerated environmental change, and also how (and whether) effective ecosystem management or restoration can reverse these trends. Most of her research is focused on stream and wetland ecosystems within urban and agricultural landscapes. Dr. Bernhardt was the coordinator of the National River Restoration Science Synthesis and served as a member of the Ecological Society of America's Visions committee. She currently serves on the External Advisory Board for the Southeastern Division of Environmental Defense, the Science Advisory Board of the Center for the Environmental Implications of Nanotechnology, and as a consultant to the Sierra Club, Earth Justice, and the Southern Environmental Law Center on issues related to water quality degradation and river and wetland restoration and mitigation.

William E. Dietrich, NAS, is a professor in the Department of Earth and Planetary Science at the University of California, Berkeley. He also has an appointment in the Department of Geography and the Earth Sciences Division of the Lawrence Berkeley National Laboratory, and is affiliated with the Archeological Research Facility. He is co-founder of the National Center for Airborne Laser Mapping and a member of the National Center for Earth-surface Dynamics. His Berkeley-based research group is focusing on mechanistic, quantitative understanding of the form and evolution of landscapes and the linkages between ecological and geomorphic processes. He has numerous publications and honors, including being named a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences, both in 2003. Dr. Dietrich received his B.A. from Occidental College, and his M.S. and Ph.D. from the University of Washington.

Dara Entekhabi is a professor in the Department of Civil and Environmental Engineering and the Department of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology. His research interests are in the basic understanding of coupled surface, subsurface, and atmospheric hydrologic systems that may form the bases for enhanced hydrologic predictability. More specifically, his current research is in land-atmosphere interactions, remote sensing, physical hydrology, operational hydrology, hydrometeorology, groundwater–surface water interaction, and hillslope hydrology. He was founding chair of the WSTB's Committee on Hydrologic Science, and has served on the WSTB and the Committee to Assess the National Weather Service Advanced Hydrologic Prediction Service Initiative program. He received his B.A. and M.A. degrees from Clark University and his Ph.D. degree in civil engineering from the Massachusetts Institute of Technology.

Graham E. Fogg is professor of hydrogeology in the Department of Land, Air and Water Resources at the University of California, Davis. His research interests include groundwater contaminant transport; groundwater basin characterization and management; geologic and geostatistical characterization of subsurface heterogeneity for improved pollutant transport modeling; numerical modeling of groundwater flow and contaminant transport; the role of molecular diffusion in contaminant transport and remediation; long-term sustainability of regional groundwater quality; and vulnerability of aquifers to non-point-source groundwater contaminants. He was the 2002 Birdsall-Dreiss Distinguished Lecturer awarded by the Geological Society of America Hydrogeology Division. Dr. Fogg co-developed the graduate program in hydrologic sciences at the University of California, Davis, using the 1991 National Research Council (NRC) report *Opportunities in the Field of Hydrologic Sciences* as a reference. He currently serves as the chair of the program. Dr. Fogg received his B.S. in hydrology from the University of New Hampshire, his M.S. in hydrology from the University of Arizona, and his Ph.D. in geology from the University of Texas at Austin.

Efi Foufoula-Georgiou is the University of Minnesota's McKnight Distinguished Professor in the Department of Civil Engineering and the Joseph T. and Rose S. Ling Chair in Environmental Engineering. She is Director of the National Science Foundation (NSF) Science and Technology Center "National Center for Earth-surface Dynamics" and has served as director of St. Anthony Falls Laboratory at the University of Minnesota. Her area of research is hydrology and geomorphology, with special interest in scaling theories, multiscale dynamics, and space-time modeling of precipitation and landforms. She has served as associate editor of *Water Resources Research*, the *Journal of Geophysical Research*, *Advances in Water Resources*, and *Hydrologic and Earth System Sciences*, and as editor of the *Journal of Hydrometeorology*. She has also served as chair-elect of the Board of Directors of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. and as member of national and international advisory boards, including the WSTB, NSF, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and European Union advisory panels, and in several NRC studies. Dr. Foufoula-Georgiou is a Fellow of the American Geophysical Union and the American Meteorological Society and an elected member of the European Academy of Sciences. She received a diploma in civil engineering from the National Technical University of Athens, Greece, and an M.S. and Ph.D. in environmental engineering from the University of Florida.

William J. Gutowski, Jr., is professor of meteorology in the Department of Geological and Atmospheric Sciences at Iowa State University. His research is focused on the role of atmospheric dynamics in climate, with emphasis on the dynamics of the hydrologic cycle and regional climate. Dr. Gutowski's research program entails a variety of modeling and data analysis approaches to capture the necessary spatial and temporal scales of these dynamics and involves working through the Regional Climate Modeling Laboratory at Iowa State University. His work also includes regional modeling of Arctic, African, and East Asian climates and involves collaboration with scientists in these regions. He served on the NRC's Committee on Climate Change and U.S. Transportation. Dr. Gutowski is a Lead Author for the Intergovernmental Panel on Climate Change FifthAssessment Report and was a Contributing Author on the Third and Fourth Assessment Reports. He was also a member of the U.S. Climate Change Science Program panels (2005-2008). Dr. Gutowski received a Ph.D. in meteorology from the Massachusetts Institute of Technology and a B.S. in astronomy and physics from Yale University.

W. Berry Lyons is a professor and the Director of the School of Earth Sciences at The Ohio State University. Previously he was a faculty member at the University of New Hampshire, the University of Nevada, Reno, and the University of Alabama, Tuscaloosa. He served as The Ohio State University Director of the Byrd Polar Research Center from 1999 to 2009. Dr. Lyons' research interests include environmental geochemistry of trace metals, such as mercury; the causes and rates of chemical weathering and landscape change; the dynamics of carbon in the terrestrial environment; the role of agriculture and urbanization on water resources; and the impact of climate change on polar ecosystems. Dr. Lyons is a fellow of the Geological Society of America, the American Association for the Advancement of Science, and the AGU. He is a past member of the NRC's Polar Research Board, and past chair of the NRC Committee on Designing an Arctic Observing Network. Dr. Lyons received a B.A. from Brown University, and an M.Sc. and Ph.D. from the University of Connecticut.

Kenneth W. Potter is a professor of civil and environmental engineering at the University of Wisconsin, Madison. Dr. Potter's teaching and research interests include hydrology and water resources, including hydrologic modeling, estimation of hydrologic risk, estimation of hydrologic budgets, watershed monitoring and assessment, and hydrologic restoration. He is a Fellow of the American Association for the Advancement of Science and the AGU, and a Woodrow Wilson fellow. Dr. Potter is a past member of the WSTB and has served on many of its committees, including the standing Committee on Hydrologic Science. He received his B.S. in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from Johns Hopkins University.

Scott W. Tyler is a professor in the Department of Geological Sciences and Engineering at the University of Nevada, Reno. Dr. Tyler's areas of focus span the wide range of arid region hydrology, with particular interest in bridging the gap between hydrogeology and soil physics in the newly emerging area of vadose zone hydrology. His work has long been focused on studies of moisture flux and groundwater recharge in arid environments. Recently, his group has been developing fiber-optic temperature sensing (DTS) to a wide range of environmental and hydrologic questions, in collaboration with researchers from Oregon State University, the U.S. Geological Survey, and the University of Delft. Dr. Tyler has focused on educating U.S. students on the problems and issues faced by citizens of developing countries with respect to safe drinking water. He leads volunteer graduate and undergraduate trips to Chile, Haiti, and, soon, to West Africa to train local villagers in well drilling and well repair. Dr. Tyler received his B.S. in mechanical engineering from the University of Connecticut, his M.S. in hydrology from the New Mexico Institute of Mining and Technology, and his Ph.D. in hydrology/hydrogeology from the University of Nevada, Reno.

Henry J. Vaux, Jr., is Professor Emeritus of Resource Economics at the University of California in both Berkley and Riverside. He is also Associate Vice President Emeritus of the University of California system. He also previously served as director of California's Center for Water Resources. His principal research interests are the economics of water use, water quality, and water marketing. Prior to joining the University of California, he worked at the Office of Management and Budget and served on the staff of the National Water Commission. Dr. Vaux has served on the NRC committees on Assessment of Water Resources Research, Western Water Management, Ground Water Recharge, and Sustainable Underground Storage of Recoverable Water. He was chair of the WSTB from 1994 to 2001. He is a National Associate of the National Academies. Dr. Vaux received an A.B. from the University of California, Davis, in biological sciences, an M.A. in natural resource administration, and an M.S. and Ph.D. in economics from the University of Michigan.

Claire Welty is the director of the Center for Urban Environmental Research and Education and Professor of Environmental Engineering at University of Maryland, Baltimore County (UMBC). Dr. Welty's work has primarily focused on transport processes in aquifers; her current research interest is in watershed-scale urban hydrology, particularly in urban groundwater. Prior to her appointment at UMBC in 2003, Dr. Welty was a faculty member at Drexel University for 15 years, where she taught hydrology and also served as Associate Director of the School of Environmental Science, Engineering, and Policy. Dr. Welty is past chair of the WSTB and has previously served on several NRC study committees, including serving as chair of the Committee on Reducing Stormwater Discharge Contributions to Water Pollution. Dr. Welty received a B.A. in environmental sciences from the University of Virginia, an M.S. in environmental engineering from the George Washington University, and a Ph.D. degree in civil and environmental engineering from the Massachusetts Institute of Technology.

Connie A. Woodhouse is an associate professor in the School of Geography and Development at the University of Arizona, with joint appointments in the Department of Geosciences and Laboratory of Tree-Ring Research. Previously, she was a physical scientist at NOAA's National Climatic Data Center, Paleoclimatology Branch. Her primary research focuses on climatic and hydrologic conditions of the past 2000 years in western North America and uses tree rings to develop reconstructions of past hydrology. Another key research interest is the application of scientific information and data to resource management. Dr. Woodhouse has served on several boards and panels, including the U.S. National Committee of the International Quaternary Association, an NSF review panel, and an NRC study of the management of the Colorado River, and is an associate editor for the journal *Dendrochronologia*. Dr. Woodhouse received a B.A. in environmental education from Prescott (Arizona) College, an M.S. in geography from the University of Utah, and a Ph.D. in geosciences from the University of Arizona.

Chunmiao Zheng is currently the George Lindahl III Endowed Professor of Hydrogeology in the Department of Geological Sciences at the University of Alabama. He is also Chair Professor and Director of the Center for Water Research at Peking University in Beijing, China. The primary areas of his research are contaminant transport, groundwater management, and hydrologic modeling. He is developer of the widely used MT3DMS contaminant transport model and co-author of the textbook *Applied Contaminant Transport Modeling* published by Wiley in 1995 and 2002 and translated into Chinese in 2009. He was recipient of the John Hem Excellence in Science and Engineering Award from the National Ground Water Association in 1998 and a fellow of the Geological Society of America since 1999. He received the Birdsall-Dreiss Distinguished Lecturer award from the Geological Society of America in 2009 that took him to 70 universities and research institutions worldwide. He has served as associate editor for leading hydrology journals, including *Water Resources Research*, *Ground Water*, the *Journal of Hydrology*, and *Hydrogeology Journal*. Currently, he is a member of the Standing Committee on Hydrologic Science of the National Research Council, and president of the International Commission on Groundwater of the International Association of Hydrologic Sciences. He received a Ph.D. in hydrogeology with a minor in civil and environmental engineering from the University of Wisconsin, Madison, in 1988.