2012

Challenges and Opportunities in the Hydrologic Sciences

George M. Hornberger
Vanderbilt University

Emily Bernhardt
Duke University

WIlliam E. Dietrich
University of California - Berkeley

Dara Entekhabi
Massachusetts Institute of Technology

Graham E. Fogg
University of California, Davis

See next page for additional authors

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

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

Contents

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.

[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

[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,

[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

[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.