Report Summary

CHALLENGES AND OPPORTUNITIES IN THE Hydrologic Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

HYDROLOGIC SCIENCE IS AT THE CORE OF UNDERSTANDING THE ROLE OF WATER in the Earth system and can help improve environmental health and sustain human welfare. Furthering this understanding will require both exploratory research, to better understand how the natural environment functions, and problem-driven research, to meet needs such as flood protection, adequate supply of drinking water, irrigation, and protection against water contamination. Collaboration among hydrologists, engineers, and scientists in other disciplines will be central to meeting this challenge. New technological capabilities in remote sensing, chemical analysis, computation, high resolution data, and hydrologic modeling will enable scientists to leverage new research opportunities and advance the field in unprecedented ways over the next decade.

Hydrologic science is, at its most basic level, the science of water. Hydrologic scientists are driven by curiosity about how the natural environment functions, and the field addresses challenging questions including understanding the fundamental water processes that link the land, the ocean, and the atmosphere, with effects on the well-being of humans and ecosystems. This blend of curiosity-driven and problem-driven research offers unique opportunities for advancing the water science to meet the needs of the changing planet.

The signature of a scientific challenge is that it is compelling, both in the domain of intellectual curiosity as well in the domain of consequence for human and ecosystem welfare. This report presents three major areas which represent compelling and societally important challenges and opportunities in the hydrologic sciences: understanding the water cycle, the role of water for life, and clean water for people and ecosystems. These three areas, all equally important, offer the potential for significant progress by taking advantage of advances in theoretical understanding and new techniques, technologies, and instrumentation that have developed over the past few decades.

Opportunities in the Hydrologic Sciences

The 1991 National Research Council report **Opportunities in the Hydrologic Sciences,** *known as the* **"Blue Book,"** *envisioned the hydrologic sciences as a distinct geoscience and set forth a corresponding research agenda. In the years since its release, the report has stimulated discussion and activities leading to the recognition of hydrologic sciences as a separate field within the Earth Sciences. Today, hydrologic sciences extends into areas traditionally of interest to other fields and related subdisciplines.*

The Water Cycle: An Agent of Change

The water cycle—the movement of water through evaporation, transport through the atmosphere, precipitation, and river and groundwater flow—is central to the processes that formed Earth and continue to influence its evolution. Understanding how water has acted throughout the history of Earth, and how water cycles work on other planets, will broaden understanding of how earth's water cycle functions.

Human Influences on Water Availability and Distribution

Over the twentieth century, human actions to meet increasing water demands from agriculture, transportation, and industry have "replumbed" the hydrologic cycle. For example, intensive groundwater pumping and the construction of large reservoirs and water diversion projects to support population growth and development have altered ground- and surface water supplies (see **Figure 1**).

At the same time, warming temperatures and shifting precipitation patterns due to climate change have also impacted the water cycle, prompting questions about how future climate change will influence the duration, severity, and extent of floods and droughts, how water distribution and availability is affected by

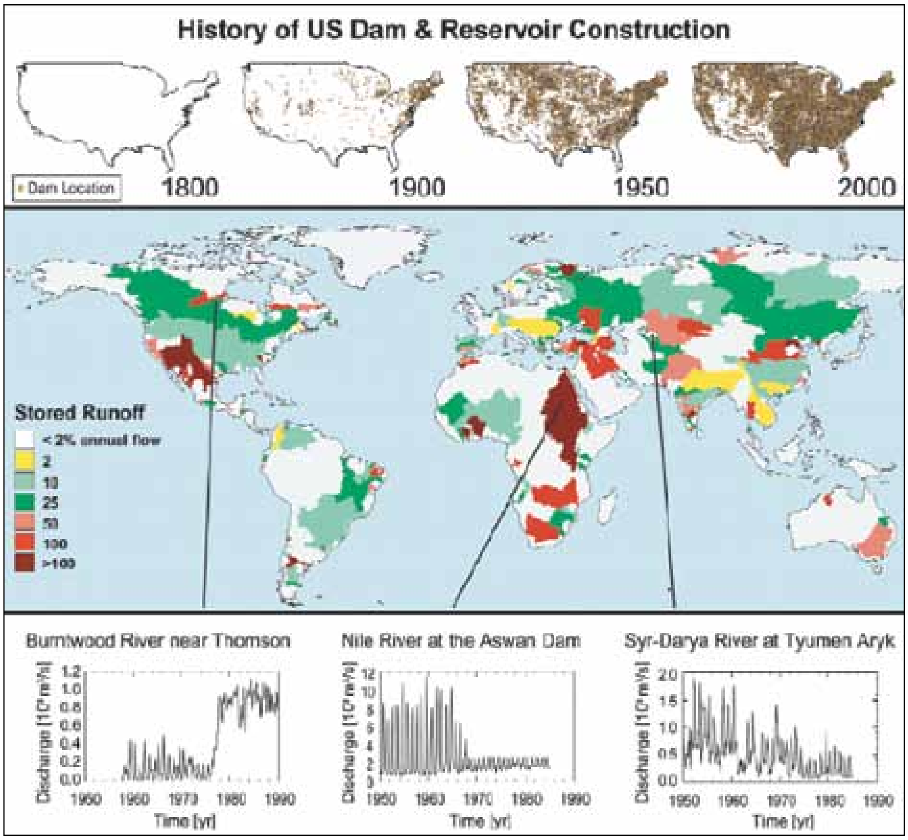

FIGURE 1. THE CONSTRUCTION OF DAMS AND CANALS HAS TRANSFORMED THE GLOBAL WATER CYCLE.
In the United States, the geographical extent of dams and reservoirs has increased dramatically over the past 200 years (top). This trend extends to other developed parts of the world, with river regulation expanding rapidly in the 20th century (middle). Water infrastructure and increasing water use have altered groundwater supplies (bottom). The graph on the left shows interbasin transfer for hydroelectric production, the middle graph shows the impact of the Aswan High Dam on the Nile River, and the right-hand graph shows flow depletion due to cotton production in the Aral Sea contributing basin. SOURCE: Vörösmarty et al. (2004) American Geophysical Union.

land use change, and how regional climate change projections can be developed and used in planning. Understanding how hydrologic fluxes will change in response to replumbing is critical to provide and maintain water supplies for humans and the environment.

Critical and Unknown Hydrologic Fluxes

Water moves via evaporation from the ocean or land surface, transpiration from vegetation, and through soils into groundwater aquifers. These hydrologic fluxes connect the water, energy, and biochemical cycles and help regulate climate, transport nutrients and sediment, and replenish aquifers. Understanding of the movement of water over large regions is incomplete, and direct information on the patterns and dynamics of evaporation, transpiration and groundwater fluxes is needed. Remote sensing measurements, ground-based measurements, and modeling will help develop this understanding.

Understanding Variability at Multiple, Coupled Scales

The many processes that define water fluxes range in scale from turbulent gusts of wind to large weather systems, and from the first drops of water that initiate streams to the complex river systems that define drainage basins. Over the past few decades, there have been major advances in understanding and modeling hydrologic processes such as precipitation, soil moisture, and streamflow, and in developing conceptual frameworks for describing variability across a wide range of scales (known as scaling theories). Areas where challenges still exist include understanding how processes at small scales interact with those at larger scales to contribute to the hydrologic response. This includes uncovering scaling laws for specific rainfall-runoff events and understanding how human replumbing of the landscape impacts hydrology, from small to large watershed scales.

CHALLENGES AND OPPORTUNITIES IN THE HYDROLOGIC SCIENCES—AT A GLANCE

The committee identified three major areas that define exciting challenges in hydrologic sciences today: **1) The Water Cycle: An Agent of Change, 2) Water and Life,** *and* **3) Clean Water for People and Ecosystems.** *Research opportunities in each of these areas are listed here in abbreviated form.*

1. **Research opportunities to better understand the water cycle** include understanding:
   - The change in hydrologic fluxes as a result of planetary replumbing;
   - The processes linking components of the hydrologic cycle, specifically, evapotranspiration and recharge;
   - The causality of subtle shifts and regime changes in streamflow and understanding the environmental impact of these changes;
   - The hydrologic response to both abrupt changes of climate and land cover over short time scales and to slow response over multidecadal to millennial and longer time scales;
   - The hydrologic processes on other planets ("exohydrology").
2. **Research opportunities at the nexus between water and life** include understanding:
   - How key hydrologic processes affecting the co-evolution of life and the planet;
   - How topography, terrestrial, and aquatic ecosystems and the hydrologic processes that connect them may co-organize over geomorphic time scales (time scales over which landforms are shaped);
   - How subsurface biota are controlled by and how they influence hydrologic processes;
   - The complex ways in which flow regimes impact critical ecological processes and the maintenance and dispersal of aquatic taxa (species) in aquatic ecosystems;
   - The processes that determine transitions in ecosystems;
   - Hydroecologic (the relationship between water and plant and animal communities) outcomes from conservation and restoration management decisions.
3. **Research opportunities related to providing clean water for people and ecosystems** include understanding:
   - The movement of contaminants through an irregular and interconnected world;
   - How contaminants interact with hydrologic processes and, in turn, impact stream ecosystems;
   - Water quality impacts of large scale drivers such as climate change, the water energy nexus, agriculture, and urbanization.

Timescales of Hydroclimatic Variability and Change

Some changes in the climate system occur over long time scales, but others occur more rapidly. Both patterns of change can result in hydrologic changes (see **Figure 2**), such as more frequent and severe floods or droughts. Understanding the hydrologic response to both abrupt and gradual changes in climate is critical for generating future scenarios of hydrologic variability and human impacts on climate, and for helping scientists anticipate the range of hydrologic variability Earth might experience in the future.

Exohydrology—Water on Other Planets

Exohydrology, the study of hydrologic processes on other planets, could yield a better understanding of the evolution of other planets and insight into how Earth works. Although the fluids on other planets may be different (for example, liquid hydrocarbons on Titan), precipitation, surface runoff, and subsurface flow can still occur, and the hydrologic observational methods and models developed on Earth are valuable to study these processes on other planets. Two research areas offer particular challenges: defining rain and surface water patterns on other planets, and estimating the magnitude, duration, and frequency of surface waters from the form and structure of the planet surface alone.

Water and Life

The evolution of life on Earth likely began with the formation of liquid water and has been shaped by water ever since. Water is essential for most organisms, and on land, the timing and the magnitude of water supply is an important force in structuring ecosystems. Over geologic timescales, changes in hydrology have been a major force in natural selection. Across the modern Earth, annual precipitation and temperature help explain variations in vegetation cover and the distribution of organisms.

Deep-Time Landscapes

Landscapes, hydrologic processes, and ecosystems evolved together throughout Earth's history, but the relative importance and rates of these processes has changed dramatically through time. For example, 4 billion years ago land plants did not exist, and therefore the influence of plants on the flux of water between Earth and the atmosphere was absent. The subsequent evolution of land plants radically changed the Earth's hydrologic system. Challenges still exist in reconstructing climate throughout Earth's history. Hydrologic science is central to providing insight on the co-evolution of life, water, and the physical landscape on Earth.

The Hydrology of Terrestrial Ecosystems

Although the flow and availability of water shapes ecosystems, living organisms also influence the water cycle and global climate. For example, in arid and semiarid climates, water limitation is a major determinant of vegetation patterns. In such environments, plants may create conditions favorable to their survival by influencing soil characteristics that alter surface water infiltration, moisture retention, and erosion. There is still much more to learn about how hydrology drives environmental patterns on Earth, for example, understanding and predicting abrupt change in terrestrial ecosystems—and how such ecological changes might affect the water cycle.

Subsurface Ecosystems and Hydrologic Processes

There is likely more life below the Earth's surface than above it. The diversity of subsurface life is staggering; just a few grams of soil could contain thousands of species, and life extends far into the weathered rock zone and even into bedrock. Subsurface ecosystems form their own environments, many challenges exist in probing how these ecosystems create and direct hydrologic pathways, release gases to the atmosphere, and control access to moisture and nutrients to aboveground ecosystems.

FIGURE 2. FLOWING MELTWATER ON THE SURFACE OF THE GREENLAND ICE SHEET, THE IMPACT OF CLIMATE CHANGE ON HYDROLOGIC PROCESSES.
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 with time. SOURCE: Roger Braithwaite, University of Manchester and Specialiststock.com.

Critical Links in Aquatic Ecosystems

Changes in river flow alter not only the extent and quality of freshwater habitats, but also the connectivity between ecosystems. As the quality and quantity of habitats declines and freshwater systems become increasingly fragmented, aquatic and floodplain species are being lost, and the water quality of rivers and coastal zones is being degraded. The hydrologic and ecologic communities are challenged to better understand how flow regimes impact critical ecological processes and the dispersal of organisms in aquatic ecosystems.

Hydroecosystems in Transition

Many organisms are adapted to a certain range of environmental conditions, making ecosystems vulnerable to changes in conditions due to climate change and shifts in land use. For example, if temperature rises in the Arctic, trees may be able to grow farther to the north, potentially displacing the tundra ecosystems.

The processes that determine ecosystem transition are not well characterized or understood, and research is needed to understand how ecosystems will respond to climate change, in particular, the extremes of Earth's hydroecosystem (the cold regions and warm deserts). Also, low or zero flow conditions during extreme dry periods, or where water diversion reduces surface flow, can fragment freshwater habitats with negative implications for the dispersal of organisms and materials through river networks (see **Figure 3**). Measuring and modeling low flow hydrology is key to understanding how ecosystems will respond to changes in climate or flow management strategies.

Conservation and Restoration Hydroecology

There has been a fundamental shift in how society values natural processes and manages landscapes. Wetlands, once considered low quality land in need of drainage, are now recognized as critical for a range of ecosystem services from flood control to providing habitat. Rivers were once viewed mainly as large scale canals and were blocked from migration, cut off from floodplains, and depleted of sediment and water. Now efforts are underway to restore natural processes to rivers to regain aquatic ecosystem function and flood management. Scientists currently lack sufficient understanding from field studies and quantitative models to make reliable predictions about desired outcomes of various restoration projects.

FIGURE 3. LOW FLOW HYDROLOGY: GEORGIA'S LAKE LANIER RESERVOIR, FALL 2007.
With water supplies rapidly shrinking during a drought of historic proportions in fall 2007, Governor Sonny Perdue declared a state of emergency for the northern third of the state of Georgia. Georgia officials warned that Lake Lanier, a 38,000-acre reservoir that supplies more than 3 million residents with water, was less than three months from depletion. SOURCE: Pouya Dianat, *The Atlanta Journal-Constitution.*

Clean Water for People and Ecosystems

Water transports vast quantities of dissolved chemicals and suspended matter. The concentration of these constituents defines water quality, and is controlled by both natural and human-caused processes. Rain and snowmelt percolate through soil and rocks carrying dissolved chemical and organic materials into groundwater and aquifers, and water flowing over land carries sediments into rivers and streams. Human-mediated changes in land use and water allocation, as well as the use of chemicals in industry and agriculture, have impacted water quality in most hydrologic basins.

As the global population grows, demand for clean water continues to increase. There are few untapped sources of clean freshwater in the places where most people live, and work is needed to maintain water quality or restore it where it has been degraded.

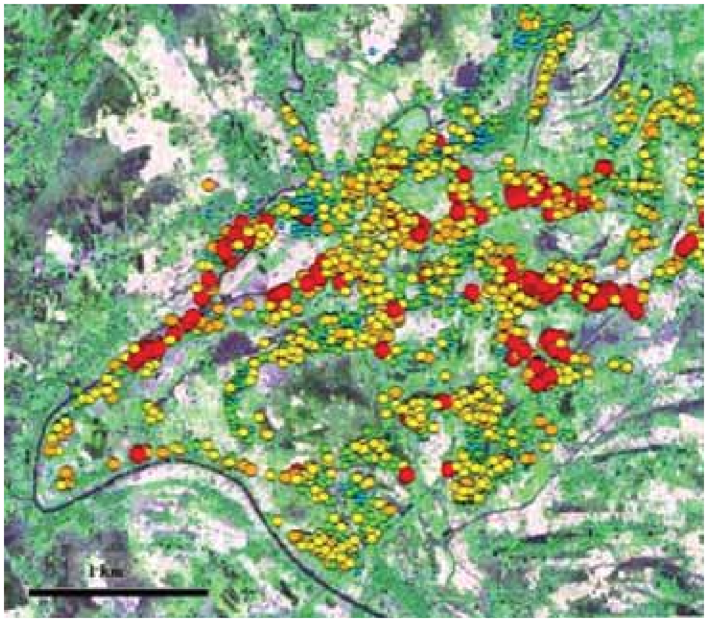

FIGURE 4. ARSENIC CONTAMINATION IN THE GROUNDWATER OF THE FLOODPLAINS OF CENTRAL BANGLADESH.
Symbols are graduated in size and color to indicate higher arsenic concentration, which varies because of complex relationships among hydrologic flow paths, sediment structure, organic carbon, and pumping. SOURCE: Beth Weinman, Vanderbilt University

Chemical Fluxes and Transformations within Complex Environments

Each landscape and ecosystem is different, and variations from the pore size of rock to irregularities in river channels can influence the flow of water and the concentration of contaminants in water. This inherent complexity makes it difficult to develop basic hydrologic principles and tools to describe the movement of contaminants in water flowing through different environments. Developing basic hydrologic principles and tools to further understand the movement of contaminants remains a challenge.

Earth's Evolving Water Quality Profile

The water quality profile of the planet is evolving as new contaminants are introduced and old contaminant use continues. Knowledge about the environmental and health impacts of "classic" contaminants—including arsenic, nutrients, lead, and chloride— is relatively well established although questions remain about the bioavailability and transport of these chemicals (see **Figure 4**). Recent advances in chemical analytical techniques have allowed scientists to identify a suite of other less studied contaminants of emerging concern. Research is needed to predict how water quality will change as new and well-known contaminants interact with hydrologic processes.

The Future of Water Quality in a Hot, Flat, and Crowded World

As Earth's population moves toward nine billion, as resource use intensifies, and as climate changes, maintaining adequate water quality will depend on new insight on these large scale drivers of water quality. A better understanding of the ways that climate change could impact water quality, for example by increasing sediment, chemical, and pathogen loading in runoff or increasing the temperature of water bodies, is also critical. Finally, research into how the increasing need for energy will impact the planet's water quality is an emerging challenge for the hydrologic and related sciences.

A Path Forward

Compelling challenges and opportunities lie ahead in understanding, quantifying, and predicting water cycle dynamics, the interaction of water and life, and how to build a path to the sustained provision of clean water for people and ecosystems. This report challenges the research community to take advantage of the opportunities at the interfaces of disciplines, engage in research that is both relevant and exciting, promote education to equip the next generation of hydrologic scientists and engineers, and to communicate this science to policy and decision makers. Some broad approaches will help the hydrologic community meet this challenge:

- **Interdisciplinarity**—There is a need for interdisciplinary hydrologic research that applies cutting edge technological capabilities to complex water related challenges of today. As technology to probe Earth's mysteries advances, computer models become more sophisticated, research relies on ever more extensive data for modeling and analysis, no single discipline will be able to advance hydrologic sciences alone. Instead, platforms and resources to allow the sharing of knowledge, equipment, models, data, and science are needed.
- **Range of Modalities**—Modalities refers to capabilities within the National Science Foundation and other federal agencies that advance hydrologic research, including contracts and research grants, instrumentation and facilities, and so forth. A range of modalities are key to tackling the challenges and opportunities in this report. For example, hydrologic science is well served by the Hydrologic Science Program within the National Science Foundation's funding of standard grants and this core research capability should be valued and nurtured. In addition, 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.
- **Education**—To meet the complex water-related challenges outlined in this report, educators should consider how best to prepare and mentor young hydrologic scientists. Scientists, engineers, and water managers will need both disciplinary depth and intellectual breadth to bridge across disciplines, and the ability to communicate their science to policy makers so that their work will make a difference.
- **Translational Science**—Multi-way interactions among scientists, engineers, water managers, and decision makers (termed "translational hydrologic science") are needed to connect science and decision making more closely to address increasingly urgent water management and policy issues.

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The National Academies appointed the above committee of experts to address the specific task requested by the National Science Foundation. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

For more information, contact the Water Science and Technology Board at (202) 334-3422 or visit http://dels.nas.edu/wstb. Copies of *Challenges and Opportunities in the Hydrologic Sciences* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.