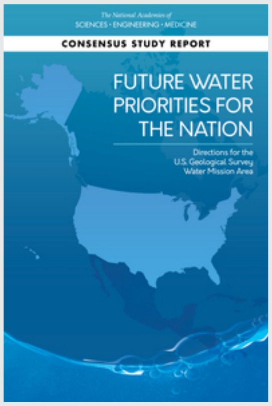

Future Water Priorities for the Nation: Directions for the U.S. Geological Survey Water Mission Area

DETAILS

110 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-47709-3 | DOI 10.17226/25134

CONTRIBUTORS

Committee on Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey; Water Science and Technology Board; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

Future Water Priorities for the Nation: Directions for the U.S. Geological Survey Water Mission Area

Committee on Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey

Water Science and Technology Board

Division on Earth and Life Studies

A Consensus Study Report of

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

PREPUBLICATION COPY

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This material is based upon work supported by the U.S. Geological Survey under Grant Agreement No. G17AP00050. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products do not constitute their endorsement by the U.S. Geological Survey. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13:
International Standard Book Number-10:
Digital Object Identifier: https://doi.org/10.17226/25134

Additional copies of this publication are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; Internet, http://www.nap.edu.

Printed in the United States of America.

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2018. *Future Water Priorities for the Nation: Directions for the U.S. Geological Survey Water Mission Area*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/25134.

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org.**

PREPUBLICATION COPY

Consensus Study Reports published by the National Academies of Sciences, Engineering, and Medicine document the evidence-based consensus on the study's statement of task by an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and committee deliberations. Each report has been subjected to a rigorous and independent peer review process and it represents the position of the National Academies on the statement of task.

Proceedings published by the National Academies of Sciences, Engineering, and Medicine chronicle the presentations and discussions at a workshop, symposium, or other event convened by the National Academies. The statements and opinions contained in proceedings are those of the participants and not endorsed by other participants, the planning committee, or the National Academies.

For information about other products and activities of the National Academies, please visit nationalacademies.org/whatwedo.

COMMITTEE ON FUTURE WATER RESOURCE NEEDS FOR THE NATION: WATER SCIENCE AND RESEARCH AT THE U.S. GEOLOGICAL SURVEY

GEORGE M. HORNBERGER (NAE), *Chair*, Vanderbilt University
KENNETH R. BRADBURY, Wisconsin Geological and Natural History Survey
YU-PING CHIN, University of Delaware
ELLEN GILINSKY, Ellen Gilinsky, LLC
PETER H. GLEICK (NAS), Pacific Institute for Studies in Development, Environment, and Security
ROBERT E. MACE, The Meadows Center for Water and the Environment, Texas State University
ANNE W. NOLIN, Oregon State University
ROGER K. PATTERSON, Metropolitan Water District of Southern California
YING FAN REINFELDER, Rutgers University
JENNIFER L. TANK, University of Notre Dame
HOWARD S. WHEATER, University of Saskatchewan

National Academies of Sciences, Engineering, and Medicine Staff

DAVID M. ALLEN, Co-Study Director, Board on Atmospheric Sciences and Climate
DEBORAH GLICKSON, Co-Study Director, Board on Earth Sciences and Resources
BRENDAN R. MCGOVERN, Research Assistant, Water Science and Technology Board
CARLY BRODY, Senior Program Assistant, Water Science and Technology Board

WATER SCIENCE AND TECHNOLOGY BOARD

CATHERINE L. KLING (NAS), *Chair*, Iowa State University
DAVID A. DZOMBAK (NAE), Carnegie Mellon University
WENDY D. GRAHAM, University of Florida
ARTURO A. KELLER, University of California, Santa Barbara
MARK W. LeCHAVALLIER, Dr. Water Consulting, LLC
DINAH LOUDA, Veolia Institute
MARGARET A. PALMER, National Socio-Environmental Synthesis Center, University of Maryland
STEPHEN POLASKY (NAS), University of Minnesota, St. Paul
DAVID L. SEDLAK (NAE), University of California, Berkeley
DAVID L. WEGNER, Jacobs Engineering
P. KAY WHITLOCK, Christopher B. Burke Engineering, Ltd.
JAMES W. ZIGLAR, SR., Van Ness Feldman

National Academies of Sciences, Engineering, and Medicine Staff

ELIZABETH EIDE, Director
LAURA J. EHLERS, Senior Program Officer
STEPHANIE E. JOHNSON, Senior Program Officer
M. JEANNE AQUILINO, Financial/Administrative Associate
COURTNEY R. DEVANE, Administrative Coordinator
BRENDAN R. McGOVERN, Research Assistant
CARLY BRODY, Senior Program Assistant

Preface

The U.S. Geological Survey (USGS) has a long and distinguished record as a source of unbiased data, information, and scientific results that support wise use and management of water resources. The "customers" of the Water Mission Area (WMA) of USGS range across a spectrum of agencies and actors, from federal, state, tribal, and local agencies, to academic research scientists, to private companies both large and small, and even to individuals who want to plan a fishing or rafting outing. For much of their work related to water resources, these customers fundamentally rely on USGS.

There is broad agreement that solving problems related to use of water resources will be of paramount importance in coming decades. In a 2017 policy statement, for example, the American Meteorological Society summarized the consensus view of scientists: "*The provision of adequate fresh-water resources for people and ecosystems will be one of the most critical and potentially contentious issues facing society and governments at all levels during the 21st century.*"[1] In the United States, the issues with which we are currently grappling—such as the widespread depletion of groundwater in the High Plains, the fact that the Colorado River rarely reaches the ocean any longer, and the persistent, harmful algal blooms in Lake Erie—are harbingers of the potential impacts that can occur in the future if steps are not taken to avoid negative consequences. The many water resources challenges of the nation have related science challenges because the data and results stemming from scientific work provide a basis for the difficult trade-off decisions that will be necessary.

Given the seriousness of looming water challenges, the work of WMA and other USGS mission areas will become even more important over the next decades and beyond as changing water resources conditions are experienced. But it would be ill-advised for WMA to spread its work thinly across all possible questions about water resources. What are the *strategic* water science and research opportunities for WMA that would address the *highest-priority* national water challenges in the future? These opportunities will evolve substantially from what they have been in the past as "big data" accumulates and as rapid advances in technology for measurement and computation continue apace. WMA will have to make wise decisions about choosing key opportunities and be flexible and nimble in order to adapt to new challenges and apply new advances as they occur. The Committee on Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey was appointed in August 2017 by the Water Science and Technology Board (WSTB) and charged with identifying key water resources challenges and the corresponding strategic opportunities for USGS, particularly WMA, over the next 25 years. This report represents the consensus views of the committee that were developed over 9 months of study. Committee members reviewed published documents and other sources of information, including material gained through interactions with selected stakeholders who routinely depend on collaboration with WMA in their work and with USGS and academic scientists.

---

[1] See https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/statements-of-the-ams-in-force/water-resources-in-the-21st-century1; accessed September 17, 2018.

I thank the members of the committee for their hard work in preparing the report, for their good-natured approach to reaching consensus on the many issues that we discussed, and for the collegiality that they exhibited throughout our work together. I also thank all the people who took time to provide input to the committee. This report, like all National Academies reports, was made possible by excellent staff work. I especially want to thank David Allen and Deb Glickson, the study directors for the project, for their 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 publication process. I also thank Brendan McGovern and Carly Brody, WSTB staff, for their incredibly hard work throughout this process. I also thank the reviewers for their helpful suggestions, which strengthened the report tremendously.

George M. Hornberger, *Chair*
Committee on Future Water Resource Needs for the Nation:
Water Science and Research at the U.S. Geological Survey

Acknowledgments

Many individuals assisted the committee and the National Academies of Sciences, Engineering, and Medicine staff in their task to create this report. The committee met four times over a 6-month period: twice in Washington, DC, once in San Diego, California, and once in Chicago, Illinois. Over the course of those meetings, the committee consulted with U.S. Geological Survey (USGS) staff and stakeholders across the nation, including those from the federal, state, and nongovernmental sectors. During its open-session meetings and through questionnaires, the committee had the opportunity to interact and learn from numerous individuals about the importance of USGS research and data to their own programs. Individuals also provided written feedback to the committee. Their voluntary engagement with the committee is an indication of the importance of input to the USGS Water Mission Area.

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Emily Bernhardt, Duke University
Efi Foufoula-Georgiou (NAE), University of California, Irvine
George Hallberg, The Cadmus Group (*retired*)
Chi Ho Sham, Eastern Research Group, Inc.
Michael Shapiro, U.S. Environmental Protection Agency (*retired*)
Norman Sleep (NAS), Stanford University
Jery Stedinger (NAE), Cornell University
Daniel Van Abs, Rutgers University
David Wunsch, Delaware Geological Survey

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **Marylynn Yates,** University of California, Riverside, and **Dick Luthy (NAE),** Stanford University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Summary

Water is essential for humans and the environment, yet maintaining and providing water in sufficient quantities and at consistently high quality is a growing challenge. Over the next 25 years, growing populations, climate change, aging water-related infrastructure, and the demands of agriculture, industry, and energy production and use will increase the need for and threaten the available quantity and quality of water supplies. Next-generation tools and technology and collaboration at multiple levels will be needed to understand changes to the water environment and determine how society can ensure clean, safe, and ample water for all uses.

The Water Mission Area (WMA) of the U.S. Geological Survey (USGS) has a long-established reputation for collecting and delivering high-quality, unbiased scientific information related to the nation's water resources. Federal, state, and local agencies, the private sector, nongovernmental organizations, academia, and the public rely on WMA for information such as water quantity and quality and use this information for several purposes, ranging from rapid responses during emergencies such as hurricanes, floods, and forest fires to the long-term management of water resources. While WMA is the nation's leader in water-related research and information, needs remain and opportunities exist to improve on the services it provides to the nation.

REPORT APPROACH

USGS asked the Water Science and Technology Board of the National Academies of Sciences, Engineering, and Medicine to assemble a panel of experts to (1) identify the nation's highest-priority water science and resources challenges over the next 25 years, (2) summarize WMA's current water science and research portfolio, and (3) provide recommendations on the strategic water science and research opportunities for WMA that would address the highest-priority national water challenges. The complete Statement of Task is presented in Box 1.1. The Committee on Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey developed this consensus study report to inform WMA on the broad, complex, and interdisciplinary challenges facing water science and resources.[1] Federal, state, and local agencies, nongovernmental organizations, industry, and other groups that work with WMA will also find this report to be of value.

The committee identified the highest-priority water science and resources challenges over the next 25 years by consulting with a wide variety of experts from the federal, state, local, nongovernmental, and academic communities. The committee agreed that the challenges of the

[1] Biographical sketches of the committee members are provided in Appendix B.

future are likely to be similar to, though likely more urgent than, those of today and that emerging technologies will help advance the response to each of these challenges, which fall into several cross-cutting categories, as noted below. Next, the committee identified 10 overarching science questions that, if addressed, would make the most significant contributions to these water science and resources challenges in the future. This set of questions was further narrowed to five priority questions that would best utilize USGS strategic scientific resources for the benefit of the nation.

WATER SCIENCE AND RESOURCES CHALLENGES

The committee identified the following water science and resources challenges, which are global in scope and encompass many interrelated issues:

- **Understanding the role of water in the Earth system:** As water moves through the atmosphere, lithosphere, and biosphere, it facilitates physical, chemical, and biological processes. Understanding how the water cycle responds and feeds back to global change remains a key challenge in Earth system research.
- **Quantifying the water cycle:** Effective management of water resources demands knowledge of how much water there is, its state, and where it is located. Quantification of the hydrologic cycle is exceedingly difficult because the stocks, flows, and residence times of water vary spatially and temporally.
- **Developing integrated modeling:** Models are essential tools for integrating and synthesizing disparate observations, for understanding complex interactions and testing hypotheses, and for reconstructing past conditions and predicting future trajectories of co-evolving systems.
- **Quantifying change in the socio-hydrological system:** Understanding how human activities influence water resources is critical to managing these resources in the United States and globally.
- **Securing reliable and sustainable water supplies:** Society is dependent on the availability of clean, reliable, and affordable surface water and groundwater for drinking water, food and energy production, industrial activities, healthy ecosystems, and recreational activities and tourism.
- **Understanding and predicting water-related hazards:** Water-related hazards represent some of the world's costliest natural disasters in both economic and human terms and are increasingly exacerbated by human activities and climate change.

QUESTIONS TO ADDRESS GLOBAL ISSUES AND ADVANCE USGS STRATEGIC SCIENCE

The committee defined 10 questions that can help address these global, interrelated challenges, and then focused on a subset for which USGS science could make the most difference. To narrow these questions, the committee developed and applied a rubric that scored questions based on the following criteria: scientific importance, societal need, relevance to the USGS mission, and relevance to USGS partners. The five questions that would have high potential to benefit USGS strategic science are:

1. **What is the quality and quantity of atmospheric, surface, and subsurface water, and how do these vary spatially and temporally?**
2. **How do human activities affect water quantity and quality?**
3. **How can water accounting be done more effectively and comprehensively to provide data on water availability and use?**
4. **How does changing climate affect water quality, quantity, and reliability, as well as water-related hazards and extreme events?**
5. **How can long-term water-related risk management be improved?**

The other five questions, while still highly important, may be addressed by the broader water research and resources communities, including USGS, as resources allow. These are:

6. **How does the hydrologic cycle respond to changes in the atmosphere, the lithosphere, and the biosphere through Earth's history and in the near future? And how do the hydrologic responses feed back to and hence accelerate or dampen the changes in the atmosphere, the lithosphere, and the biosphere?**
7. **How can short-term forecasting for climate, hydrology, water quality, and associated social systems be improved?**
8. **How do institutions and governance and institutional resilience impact the quantity and quality of water?**
9. **How can understanding of the connections between water-related hazards and human health be improved?**
10. **How can competing uses for water resources be managed and maintained to sustain healthy communities and ecosystems in a changing world?**

EMERGING AND INNOVATIVE TECHNOLOGIES

Over the next 25 years, new opportunities will emerge that will allow for observations that come from an array of sources, are more affordable, offer data from previously inaccessible locations, provide "fit-for-purpose" temporal and spatial resolution, and deliver measurements of new parameters. Associated with the wide adoption of those technologies is a need to develop systems (e.g., hardware, software, management frameworks, protocols) that can rapidly collect data from disparate sources, assess those data for quality, store and process them, and share them in near real-time in formats that are informative and accessible for users.

New space- and ground-based sensors, from drones to "lab-on-a-chip" sensors, will advance observations and analyses of water resources, but many technical challenges exist with respect to measuring and monitoring water quality. Microsensors remain an area of research and development that shows great promise, and the technology in this realm will continue to develop, improve, and become more affordable. Environmental DNA (eDNA) methods can already detect invasive species from a single sample of water; new insights into environmental health and resilience will follow. Developments in managing "big data" and integrating data from multiple sources and of different types will support improved scientific understanding, development of improved models, and interdisciplinary model integration. An area of great interest is improved coupled modeling of the natural-human water system. Projections of future human impacts and water-related risks, however, are inevitably associated with large uncertainties; therefore, a need exists to develop improved models to support decision-making under uncertainty. Improvements in water-resources data access and presentation will continue to be needed, as will the expansion of opportunities for citizen scientists to fill data gaps and supplement existing data networks through collection of basic water-quality measurements or water sampling for later analysis.

RECOMMENDATIONS FOR WMA

Based on the cross-cutting water science and resources challenges and the overarching and high-priority questions identified above, the committee arrived at the following recommendations, which are not presented in any order of importance. The committee also presents recommendations to help WMA align with USGS strategic directions and provide opportunities for collaborations among WMA and other USGS mission areas, other federal agencies, and state and local partners. These recommendations provide a framework to help guide the evolution of WMA, so that USGS can effectively address the current and future water resources challenges that will face the nation over the next 25 years. Recommendations 1.1-5.1 are numbered to reflect their relevance to the five priority questions above (e.g., Recommendation 2.1 is associated with priority question 2: "How do human activities affect water quantity and quality?"). Recommendations 6-8 are additional, overarching recommendations.

Recommendation 1.1: Enhance data collection, include citizen science, and develop Web-based analytical tools.

To enable the nation to meet future water resources challenges, WMA should (1) strategically enhance the temporal and spatial collection of water quantity, quality, and water-use data using robust, innovative technologies to develop readily accessible "fit-for-purpose" information; (2) further infuse citizen science into USGS data-collection activities to augment traditional monitoring networks; and (3) develop innovative, intuitive Web-based data analysis and visualization tools for the nation to better understand the status and trends of its water resources.

Recommendation 1.2: Coordinate with agencies and organizations on data delivery.

As part of the national effort to deliver water quantity and quality data and information, WMA should coordinate with other agencies and relevant organizations to co-develop accessible, open, and codified data formats, protocols, interoperability, and software tools. This will allow integration across data streams and encourage synthesis of multiple observations in order to detect trends, patterns, and changes in water quantity and quality.

Recommendation 2.1: Increase focus on the relationships between human activities and water.

WMA should prioritize investigations of the relationships between human activities and changes in surface water and groundwater quantity, quality, and water-related hazards through a careful synthesis of observations and coupled natural-human systems models forced by climate and socioeconomic factors.

Recommendation 3.1: Develop a robust water accounting system.

WMA should conduct studies to understand how to best and most efficiently execute water accounting and how to assess and present uncertainty in the reported data. Water accounting should go beyond measurement of the resource itself to consider the biophysical and societal constraints on water use and should include estimates of consumptive versus non-consumptive water use.

Recommendation 3.2: Collaborate with agencies and organizations on water-data standards and categories of use.

As part of the national effort to collect water-use data and information, WMA should collaborate with other agencies and relevant organizations to co-develop standards, protocols, and clear definitions for categories of water use, and should adhere to common format standards across states, counties, and watersheds.

Recommendation 4.1: Ensure that monitoring networks provide adequate information to assess changing conditions.

USGS should periodically assess the state of surface water and groundwater monitoring networks to ensure that these networks can provide data for hydrologic impact analyses as environmental conditions change due to climate, agriculture and other land uses, and urbanization.

Recommendation 5.1: Focus on long-term prediction and risk assessment of extreme water conditions.

WMA should prioritize activities that address long-term prediction and risk related to hydrologic causes such as floods, droughts, and water-borne contaminants. WMA should seek to understand how climate change, land-cover and land-use change, and other biophysical and socio-economic factors affect the nation's water resources, including water quantity and quality, extreme events, and other hydrologic hazards. USGS should further develop integrative models that can help predict future hydrologic conditions under these changing climate conditions. These activities will require integrative studies with other USGS mission areas and should include resource managers, decision makers, and social scientists.

Recommendation 6: Develop multiscale, integrated, dynamic models that encompass the full water cycle.

WMA should prioritize multiscale and integrated modeling efforts that dynamically couple above- and below-ground hydrologic stores and fluxes, water quantities and qualities, and natural and human drivers and interactions, and utilize diverse observations ranging from ground-based sensing to Earth observations from airborne and space-borne platforms.

Recommendation 7: Collaborate as appropriate both within and outside of USGS, including agencies and the private sector.

Given that water resources challenges are inherently interdisciplinary, WMA should continue to build and maintain strong collaborations. WMA should maintain and strengthen ties with other USGS mission areas to maximize the impact of its work on

observing, understanding, predicting, and delivering water data and issues. WMA should maintain and strengthen ties with other federal and state agencies, and as appropriate, international agencies (especially regarding transboundary water issues) to meet these water resources challenges. WMA should also evaluate and, where deemed advantageous, engage in private-sector collaborations to develop new data sources and platforms, and in the dissemination of data and information, models, and other products.

Recommendation 8: Build a workforce who are ready to take on new water challenges.

WMA should align its current and future workforce to meet critical strategic needs, specifically building capacity for improved water monitoring; coupled natural-human systems modeling; and data analysis, analytics, visualization, and delivery using reliable, accurate, robust, and innovative methods.

1
Introduction

Water is essential to life and is integral to the development, health, and growth of communities and ecosystems throughout the United States and the world. Water of specific qualities and quantities is needed for the production of food, energy, and industrial products; for the development and operation of infrastructure and transportation systems; and to satisfy basic human needs in all settings, from the rural to the urban. Thus, water resources are closely linked to economic development (Brown and Lall, 2006). Natural terrestrial environments and aquatic ecosystems are also critically dependent on water and its replenishment through the nation's interconnected watersheds and their various contributing rivers, lakes, streams, snowpacks, and aquifers.

In addition to daily water demands and needs for freshwater, perturbations to the hydrologic system may result in too much or too little water, causing flooding or drought. These changes to the system, often exacerbated by human-made circumstances, affect the safety, economy, and wellbeing of people in every part of the country. Flooding, for example, may occur in response to extreme precipitation, rapid snowmelt, or storm surge. In 2017, the extreme precipitation from Hurricane Harvey inundated more than 300,000 structures in Houston, Texas, causing the evacuation of hundreds of thousands of people, with the costs of flood damage from the event estimated to exceed $125 billion.[1]

Just as too much water in the wrong place at the wrong time can lead to human, economic, and ecological losses, too little water also poses risks. While there are several definitions of drought, climate and weather variability, together with human pressures on water resources, can combine to cause water scarcity. By many measures, drought risks are on the rise (e.g., Strzepek et al., 2010; Cook et al., 2015, 2018; Diffenbaugh et al., 2015). Even without the extreme variations in weather that are linked to the changing climate, growing populations and economies are placing increasingly greater pressure on water resources (Vörösmarty et al., 2000). California recently experienced a severe 5-year drought that had significant effects on forest health and fisheries and led to groundwater overdraft and cutbacks in water availability for agriculture and municipalities (Griffin and Anhukaitis, 2014; Diffenbaugh et al., 2015).

Although the United States is much better off than much of the world with respect to deleterious water-related health effects, there is still work to be done (Patel and Schmitt, 2017). Water contaminants, including microorganisms such as bacteria and viruses and chemical products produced by modern society, are consistently found in both natural waters and municipal and rural water supplies (e.g., Kolpin et al., 2002; Focazio et al., 2008; Malham et al., 2014; Campos et al., 2015), whether through natural breakdown and disposal of these substances or through accidental or intentional spillage or runoff. However, the quantities, fate, and transport of this large range of

[1] See https://www.ncdc.noaa.gov/billions/overview; accessed September 4, 2018.

contaminants are not known with certainty. With the advent of new analytical instrumentation, chemicals that were not previously detectable have been discovered in waterways. Over the past two decades, it has been shown that these emerging contaminants can pose a threat to both human and ecosystem health (e.g., Fields et al., 2006). Particularly in the case of emerging contaminants, their effects on the health of human and natural systems and the ways in which they may transform or degrade in the environment are not yet well established, in part because the ability to detect and monitor them is still developing (Richardson and Ternes, 2009).

Water, in all of its natural and constructed environments, represents a fundamental and sometimes limited resource and a continuous challenge in terms of monitoring and predicting its behavior, flow, transport, and composition. At present, the state of knowledge is incomplete relative to how the various stocks of water are organized across the landscape, how flows among them change, and how and why water quality varies temporally and spatially. Understanding the natural processes related to water, the ways humans influence and control these processes, and the related changes in water quality and quantity over time is key to sustaining human health and prosperity and maintaining environmental quality. A central opportunity for humanity in the 21st century is to understand the nature of water resources challenges and to develop and apply the solutions, both institutional and technological, capable of addressing them successfully.

THE U.S. GEOLOGICAL SURVEY AND THE WATER MISSION AREA

Water resources needs of the nation are persistent, dynamic, and require holistic approaches that depend on multiple lines of science- and engineering-based evidence to help conserve and sustain water availability for society. The U.S. Geological Survey (USGS) is a scientific agency housed within the U.S. Department of the Interior and is tasked by the U.S. Congress to provide scientific information to describe and understand geological processes; water, biological, energy, and mineral resources; natural hazards; ecosystem and environmental health; and impacts of global change. As such, USGS is the prime federal agency to inventory, monitor, and conduct scientific research on the nation's water resources.

The Water Mission Area (WMA) is one of seven interdisciplinary mission areas within USGS. WMA's strategy is to provide water resources monitoring, assessment, modeling, and research data and tools that are relevant to (1) preserving the quality and quantity of the nation's water resources; (2) balancing water quantity and quality in relation to potential conflicting uses; (3) understanding, predicting, and mitigating water-related hazards; and (4) quantifying the vulnerability of human populations and ecosystems to water shortages, surpluses, and degradation of water quality. To address this strategy, WMA collects, assesses, and disseminates hydrological data and analyzes and researches hydrological systems.

WMA works closely with federal, state, and regional partners to coordinate and conduct scientific studies and is the most important national source of basic water resources data for other federal agencies such as the Federal Emergency Management Agency (FEMA), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA; in particular, the National Weather Service), the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation, the U.S. Department of Agriculture, the U.S. Environmental Protection Agency (EPA), and other agencies within the U.S. Department of the Interior. WMA also plays an active and important role as part of the broader research community and the private and nongovernmental sectors by contributing significant data, observations, and analyses to support scientific advances and understanding with respect to water and to inform water policy and decision-making at the national, regional, state, and local levels (e.g., NRC, 2009). WMA's operational structure fosters interaction with partners at all levels and ensures that USGS provides focused and relevant national scientific expertise to states and localities. As an example, WMA is monitoring nitrate levels[2] at more than 60 sites in the Mississippi–Atchafalaya River Basin as part of the strategy to reduce hypoxic areas in the Gulf of Mexico.[3] WMA serves as a consistent national resource for advancing water science while setting critical research priorities to meet the persistent and dynamic challenges to the nation's future water systems.

As of 2018, WMA has a workforce of approximately 3,750 staff at state and regional Water Science Centers and headquarters. More than 60 percent of WMA personnel are classified as hydrologists or hydrologic technicians, with other personnel classified as administrators, biologists, chemists, computer scientists, and ecologists. As the primary federal agency for water information, WMA monitors and assesses the quantity and characteristics of the nation's water resources, investigates the sources and behavior of natural solutes and contaminants in water (often with state cooperators and partners), and develops practical tools to improve understanding and management of this resource. WMA personnel respond to strategic national priorities set by headquarters as well as regional, state, and local needs determined largely by collaborative partners. A more thorough discussion of WMA goals and capabilities is provided in Appendix A.

COMMITTEE CHARGE

In 2013, USGS released its Water Science Strategy plan, which examined societal issues and developed a strategy that "observes, understands, predicts, and delivers water science by taking into account the water science core capabilities of the USGS" (Evenson et al., 2013, p. v). Furthermore, WMA seeks to provide water resources monitoring, assessment, modeling, and research data and tools through *observing* the water cycle, improving *understanding* of critical processes, *predicting* changes in water availability and quality over time, and *delivering* water science data and information to federal, state, and local agencies, the public, tribes, and industry to support informed decision-making.[4]

To support its efforts to implement that strategy and to refine it in light of the significant water challenges the nation continues to face, USGS requested that the National Academies of Sciences, Engineering, and Medicine's (the National Academies') Water Science and Technology Board undertake a study to examine future water resources and science challenges over the next 25 years and to determine strategic research opportunities on which WMA could focus to address these challenges (see the Statement of Task in Box 1.1). With a foundation in several prior reports about water resources and the hydrologic sciences (NRC, 1991, 2009, 2012a), the National Academies convened the Committee on Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey to respond to this request. (See Appendix B for the biographical sketches of committee members.)

---

[2] See https://sparrow.wim.usgs.gov/marb/; accessed September 4, 2018.
[3] See https://www.epa.gov/sites/production/files/2017-11/documents/hypoxia_task_force_report_to_congress_2017_final.pdf; accessed September 4, 2018.
[4] Data provided to the committee by Dr. Don Cline, USGS Associate Director for Water, at the committee's first meeting on September 18, 2017.

BOX 1.1
Statement of Task

The U.S. Geological Survey (USGS) plays an essential role in meeting the nation's water resource needs through its well-established observational network and renowned water science and research activities. A study by the National Academies of Sciences, Engineering, and Medicine would provide guidance to the USGS Water Mission Area (WMA) as it works to address the most compelling national water resource and science needs during the next several decades. In particular, the study will:

1. Identify the nation's highest-priority water science and resource challenges over the next 25 years. This effort should be visionary, and should consider new science and emerging technologies.

2. Summarize the current water science and research portfolio of WMA. This summary will include describing WMA's primary roles, responsibilities, and capabilities in observing, understanding, predicting, and delivering water science; organizational infrastructure; data science, management, and hydroinformatics; range and balance of scientific and technical expertise; and primary collaborations with several U.S. government agencies (e.g., NOAA, USACE, Bureau of Reclamation, FEMA, and others), state and local government agencies, academic institutions, nongovernmental organizations, and the private sector.

3. Provide recommendations on the strategic water science and research opportunities for WMA that would address the highest-priority national water challenges identified in (1) and would have high potential to benefit USGS strategic science and other U.S. government priorities. This analysis will include discussion about tools WMA may employ for observing, understanding, predicting, and delivering water science, and will identify opportunities for collaboration between WMA and other mission areas in USGS, and other entities (e.g., U.S. government agencies such as NOAA, USACE, Bureau of Reclamation; state; local; and academic institutions).

The study will consider opportunities for integrating across disciplines and will address water science and research at multiple scales. The final report will provide visionary guidance on what directions WMA should pursue to be most relevant to society over the next several decades.

A VISION FOR THE FUTURE

All components of the water cycle continually respond and adjust to change, from local to global scales. Over the next 25 years, the technological landscape (including data and modeling) will look substantially different, and the capability to access and visualize complex data will be commonplace. In terms of water resources, high-resolution models will integrate data from dense arrays of ground-based and satellite sensors and remotely sensed measurements, and will in turn provide accurate, real-time, globally available data products. These products will include not only customizable and specialized current and forecast precipitation, surface water flows, groundwater levels, and water quality, but also emergency warnings for floods, droughts, and related hazards.

From a societal perspective, stronger integration of natural and social sciences with hydrological, climatological, and ecological analyses will improve understanding of the values, governance, and instruments that underlie water policy and management, including the needs and tradeoffs among important water-use sectors. Directed water research will deepen understanding of the human health and ecosystem consequences of water-related risk, whether from emerging or known contaminants (including pesticides and pharmaceuticals), increased coastal flood risk, contaminated floodwaters, water-related diseases, or drought.

With these thoughts in mind, the committee developed a concise vision to help guide its approach:

> *The challenges of providing water of adequate quantity and quality for all uses and of providing protection from water-related hazards are well recognized today. These challenges will expand in importance over the next 25 years. Technological and institutional advances and integrated and interdisciplinary approaches and policies will provide water scientists and managers with the tools they need to meet these challenges.*

COMMITTEE APPROACH

The committee convened three information-gathering meetings (September 18–19, 2017, Washington, DC; November 30–December 1, 2017, San Diego, California; February 8–9, 2018, Chicago, Illinois) and an additional closed session meeting to develop and finalize this report (April 19–20, 2018, Washington, DC). The committee heard presentations from leaders in fields related to many aspects of the Statement of Task (SOT), including those from state and federal agencies, the private sector, and nongovernmental organizations. In addition, the committee held several webinars on topics such as hydroinformatics, water management, and technological advances in water research and monitoring and gathered information from a questionnaire distributed to Water Science Center directors and to state geologists. Appendix C lists the presenters and participants at these information-gathering meetings and webinars, as well as the questionnaire respondents. The committee also consulted peer-reviewed research literature, state and federal government reports, and international documents to provide a strong scientific foundation for this report.

Although the committee heard several presentations from USGS WMA personnel about their ongoing work, a complete review of WMA programs and an evaluation of the effectiveness of current WMA programs was outside the scope of its Statement of Task (see Box 1.1). Rather, the committee focused on how new science research and emerging technologies might be used in coming decades, whether applied to current topics or to new directions for WMA, and provided suggestions for how WMA can position itself to take advantage of these changes.

The report structure is as follows: Chapter 2 identifies the highest-priority water resources and science challenges for the nation for the next 25 years (SOT 1) and Chapter 3 identifies, among those challenges, where and in which formats WMA can add unique value through its scientific work (SOT 3). Appendix A provides a high-level summary of WMA activities and partnerships (SOT 2).

2
Water Science and Resources Challenges for the Next 25 Years

The United States and the world face critical issues that put increasing pressure on water resources, including growing populations, climate change, extreme weather, aging water-related infrastructure, and demands for food, energy, and industrial production. These issues can create threats to water quantity and quality and result in greater exposure to hydrologic extremes and hazards, affect economic and policy decisions, and exacerbate the balance of tradeoffs between human and ecological water uses and needs. Scientific and technological advances to help quantify, characterize, understand, and predict water resources will be key to address these issues nationally and globally, helping inform and support balanced water use, management approaches, and access to safe water for people and ecosystems.

The Water Mission Area (WMA) tasked the committee to identify the highest-priority water science and resources questions for the United States over the next 25 years. As it considered this quarter-century perspective, the committee spent considerable time deliberating about whether the pressing water issues of today will still be relevant in 25 years or whether an entirely new set of water science and resources questions will emerge. The committee's consensus is that the fundamental water issues of today, as well as their societal relevance, will only become more significant and far-reaching as time proceeds.

As part of its information gathering, the committee considered the significant body of work represented in previous National Research Council reports such as *Toward a Sustainable and Secure Water Future: A Leadership Role for the U.S. Geological Survey* (NRC, 2009), *Global Change and Extreme Hydrology* (NRC, 2011), *Challenges and Opportunities in the Hydrologic Sciences* (NRC, 2012a), and *Preparing for the Third Decade of the National Water-Quality Assessment Program* (NRC, 2012d). The committee also discussed a wider variety of water science and resources issues with experts and stakeholders from government agencies, academia, and nongovernmental organizations.

On the basis of these resources, coupled with its knowledge and additional background research, the committee identified six cross-cutting water challenges:

- **Understanding the role of water in the Earth system;**
- **Quantifying the water cycle;**
- **Developing integrated modeling;**
- **Quantifying change in the socio-hydrological system;**
- **Securing reliable and sustainable water supplies; and**
- **Understanding and predicting water-related hazards.**

A discussion of each of these challenges is presented below. Another theme that was consistently raised by the spectrum of stakeholders who provided input to the committee was the continuing, rapid expansion of technologies to observe, process, and visualize water-related information. Based on consideration of these six water science and resources challenges and the opportunities provided by technological advances, the committee compiled a set of high-priority science questions to address the challenges. These priority questions are presented in the last section of this chapter.

WATER SCIENCE AND RESOURCES CHALLENGES

Understanding the Role of Water in the Earth System

The water cycle is of central importance in Earth system functions and is a primary driver of energy and biogeochemical cycles (e.g., Eagleson, 1986). As water moves through the atmosphere, the lithosphere, and the biosphere, it facilitates many physical, chemical and biological processes and carries with it latent heat, sediment, nutrients, and carbon that regulate the Earth's climate system from diurnal to geological time scales (Schlesinger and Bernhardt, 2013; Korenaga et al., 2017). The hydrologic cycle has undergone profound changes throughout Earth's history, responding to changes in the atmosphere (e.g., radiative budget from orbital and greenhouse gas forcing), the lithosphere (e.g., plate tectonics, orogeny, subsidence, weathering), and the biosphere (e.g., evolution and upland colonization of land plants, the emergence of angiosperms). Changes in the hydrologic cycle feed back to the energy and biogeochemical budgets of the atmosphere, the lithosphere, and the biosphere through complex interactions (Clark et al., 2015; Good et al., 2015). Understanding how the water cycle responds and feeds back to global change in the past and in the near future, and with increasing human pressure on water and other parts of the global system, remains a key challenge in global change research (Haddeland et al., 2014; Kaushal et al., 2014). It also presents opportunities to transform the knowledge and improve the predictive capabilities of the Earth as a system. This fundamental scientific knowledge is needed for the effective management of water resources.

Quantifying the Water Cycle

Effective management of water resources demands knowledge of where and how much water exists in key stocks (e.g., in glaciers, snowpacks, aquifers, lakes, rivers, soils) and how water moves within and among these different stocks (NRC, 2012a). Quantifying the water cycle is exceedingly difficult because the stocks, flows, and residence times of water vary spatially and temporally, as do the relevant parameters that influence their residence time and location (e.g., soil, land cover, aquifer characteristics, topography, dam and reservoir management, agricultural practices). Accurate measurements of the physical and chemical properties of water are needed, as well as an understanding of the biogeochemical transformations that affect water quality (Michalak, 2016). Land-cover and land-use change, infrastructure such as dams and levees, and climate change intersect with and alter the water cycle, adding more complexity to efforts to quantify it.

Developing Integrated Modeling

Models are essential tools for integrating and synthesizing disparate observations, for elucidating complex interactions and testing hypotheses, and for reconstructing past conditions and predicting future trajectories of co-evolving systems. Models can aid in assessing the potential for rapid environmental change and can help harness vast amounts of data in visually compelling ways that can provide information to decision-makers. Historically, hydrologic simulation has focused on individual components of the hydrologic cycle (e.g., groundwater models, surface water models); consequently, an urgent need exists for improved, integrated models of water systems (Davies and Simonovic, 2011). Such models can simulate multiple parts of the hydrologic cycle simultaneously, and build on the explosion of information and advances in data and computation technology. These models can ideally link to other models of the terrestrial system, such as those for land use and land-use change, ecosystems, and the biosphere; geochemical components such as carbon and nitrogen; and the atmosphere, including weather.

These types of integrated models are needed as society faces mounting pressure over competing demands for limited natural resources and the need to improve predictive capabilities of the state and behavior of the water system, as well as the delivery of that knowledge to users. Integrated modeling for water will need to link groundwater and surface water (Refsgaard et al., 2010); provide measurements of water quantity and quality, land-atmosphere feedbacks, and precipitation; and represent human decisions explicitly (Davies and Simovic, 2011; Jaeger et al., 2017). Such models will need to be constrained by observations (NRC, 2008) and provide outputs that can be tuned to user needs at a range of scales (Garcia et al., 2016).

Given the complexity and range of spatial-temporal scales of water movement through the hydrologic cycle, it may be impractical to integrate all stocks and fluxes in a single model, especially when also integrating complicated, scale-dependent suites of natural and human drivers and feedbacks. The challenge will be to formulate problem-driven conceptual models that identify key drivers and responses at relevant scales and to remove barriers among different disciplines (e.g., vadose zone, surface water, groundwater, water quantity, and specific quality) to develop integrated modeling approaches.

The National Water Model (NWM) is one example of the potential for integrated water models to help support and enhance decisions about flooding, droughts, and other societal risks in real-time (see Box 2.1). This integrated model was recently developed jointly by the National Oceanic and Atmospheric Administration's (NOAA's) Office of Water Prediction, the National Center for Atmospheric Research (NCAR), the academic community (i.e., Consortium of Universities for the Advancement of Hydrologic Sciences, Inc.), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), and other federal agencies.

BOX 2.1
The National Water Model

The National Water Model (NWM) is designed to forecast streamflow in real-time across the nation by mathematically describing the physics of water movement from precipitation to streamflow. The input variables include real-time analysis and assimilation of precipitation data, USGS streamgage information, and land-surface properties such as terrain slope and river channel morphology. The output variables are streamflow in real-time with 18-hour, 10-day, and 30-day lead times at millions of stream reaches across the nation.

Compared with the early generation of river forecast models, the NWM is being developed to predict not only high flows and flooding, but also low flows and drought conditions, and has expanded the number of stream reaches along which these forecasts can be made from less than 4,000 to more than 2.7 million. The NWM is built on an Earth system modeling platform—the NCAR Water Research and Forecasting Hydrologic Model (WRF-Hydro) framework—which enables modular development and multiple, new process coupling in the future, such as water quality forecasting.

USGS played an important role in the conception of the NWM and continues to be a key partner in its ongoing design, development, and testing. The current version of the NWM assimilates streamflow observations provided by USGS at more than 7,000 streamgages. USGS is leading the development of the subsurface model to simulate soil water and groundwater movement, the latter buffering flooding and providing baseflow to streams. USGS is also envisioned to play a critical role in providing foundational datasets such as subsurface porosity and permeability. Opportunities exist to integrate new and innovative approaches to mapping subsurface geology and hydrostratigraphy in three dimensions, which could provide natural links to other USGS activities such as the National Cooperative Geologic Mapping Program. USGS could also help to improve the NWM through additional data collection, which could be used to test and validate the model, and through incorporating management complexities in the nation's rivers, such as reservoir operations.

Quantifying Change in the Socio-Hydrological System

Human activities and actions can affect water resources in a variety of ways. Water infrastructure and its operations (e.g., dams, groundwater wells), coupled with urban and agricultural land-use change, can affect water quantity and quality; while land-use management practices and contaminants from human activities also alter its quality. These activities influence water resources availability and quality across the United States and globally (Gleick, 2003a; Nilsson et al., 2005), and can reduce or enhance flood risks. For example, global changes in the freshwater discharges from land to the oceans are a reflection of alterations to the hydrologic cycle in response to climate change (Syed et al., 2010; Durack et al., 2012) and to continued human alteration of water flows through ongoing reservoir construction (Chao et al., 2008). Changes in climate that result in warmer temperatures, stronger storms, more droughts, and changes to water chemistry can further alter water quality (Georakakos et al., 2014). These effects, and others such as nutrient pollution leading to harmful algal blooms (including cyanobacterial), can influence the economy by affecting riparian development, ecosystem health (and their services), recreation and tourism, water treatment, and public health and well-being (Repetto, 2012; Michalak, 2016).

Securing Reliable and Sustainable Water Supplies

Society depends on the availability of clean and reliable surface water and groundwater for the provision of safe drinking water, food and energy production, industrial water supply, healthy ecosystem functions, and support of recreational opportunities and tourism (NRC, 2012a). Reliability of water resources, in turn, depends on efficient and effective infrastructure for water delivery and conservation (EPA, 2016). The impact of extreme weather events such as drought and floods, as well as the effects of climate change, represent threats to water resources (Boehlert et al., 2015). In addition, natural and managed water systems are increasingly affected by land and water management decisions (NRC, 2009).

To manage water resources in ways that can meet societal and environmental needs, the amount of water available has to be quantified and the reliability of water sources in the face of pressures from extreme events and failing infrastructure has to be understood (Gleick et al., 2013). Real-time information is also needed to effectively manage these resources to guard against overuse. A sound science base can inform management decisions regarding aquatic ecosystems that have to respond to changing flow regimes and water quality (Vörösmarty et al., 2010; NRC, 2015, 2016). In addition, ensuring that environmental flows of water are adequate necessitates interdisciplinary work to quantify ecosystem habitat and processes (Novak et al., 2016). Considering water resources in the context of integrated resources management can bring an integrative understanding of the feedbacks between water and these other resources that will ultimately affect water security (Barthel and Banzhaf, 2015).

Understanding and Predicting Water-Related Hazards

Water-related hazards represent some of the world's costliest natural disasters in both economic and human terms (see Box 2.2) and are increasingly exacerbated by human activities and global change. Scenarios of climate change predict, for example, that the United States will see an increase in heavy precipitation, regionally varying changes in flood hazard, and increased risk of chronic long-term drought in the western United States (USGCRP, 2017). Understanding these complex interactions, managing the effects of human activities on water-related hazards and extreme events, and communicating the associated risks for lives, livelihoods, and the environment will need science informed by high-quality, long-term data and analysis and high-resolution modeling tools. Impacts from human activities are not limited to climate; for example, widespread use of de-icing salt on roadways in the northern United States has resulted in increased chloride concentrations in freshwaters, which can degrade ecosystems and compromise drinking water. The highest contamination is associated with urban land use and impervious surfaces (Boutt et al., 2001; Kaushal et al., 2005). Better understanding of local impacts can also be complemented by increased understanding of large-scale feedbacks and the implications for atmospheric and terrestrial systems. Understanding the hydrological impacts of humans on water-related hazards is a continuing challenge (Gleick et al., 2013).

BOX 2.2
Water Related Hazards and Their Impacts

Too much or too little water can be immensely damaging. California's 5-year drought (2012–2016) caused a range of environmental and economic effects, including disruptions to agricultural production and access to domestic water, loss of hydropower (which led to a $2.5 billion increase in electricity costs), and major drawdown of groundwater resources (Mann and Gleick, 2015; Gleick, 2017). This followed Texas' worst 1-year drought on record in 2011, which harmed agricultural production and crop prices (Nielsen-Gammon, 2012). New York City suffered $19 billion in damages from Superstorm Sandy, which led to the adoption of flexible adaptation plans for the future (Rosensweig and Solecki, 2014). Such disasters affect human health, infrastructure, and social functions, as well as agricultural and industrial production, and can have regional and even global economic consequences. Severe flooding in Thailand in 2011 was estimated to have caused $46.5 billion in economic losses due to disruption of global supply chains for key electronic components (World Bank, 2012).

Extreme weather can have direct effects on soil moisture, river flows, and groundwater, as well as degradation of water quality. Extreme precipitation events include freezing rain in winter climates, which can disrupt transport and threaten powerlines that supply large populations. Water-quality hazards arise from short-term accidental releases, such as a pipeline break, long-term release of pollution from contaminated sites, or non-point source pollution from nutrients (e.g., Kling et al., 2011; Michalak, 2013; Jetoo et al., 2015; Compton et al., 2016; Steffen et al., 2017). Hurricane Harvey even affected groundwater when contaminated floodwaters seeped into water wells (Stuckey, 2017). These direct effects may have multiple and interconnected secondary outcomes, such as landslides from excess rain, pest outbreaks, dust storms, and wildfires due to drought.

EMERGING TECHNOLOGIES

New technologies will emerge over the next 25 years that will allow for observations that come from a wide variety of sources, are more affordable, offer previously inaccessible location data, provide "fit-for-purpose" (i.e., designed to meet the specific requirements of its intended purposes) temporal and spatial resolution, and deliver measurements of new parameters. Together with the wide adoption of those technologies, there will be a need to develop systems (e.g., hardware, software, management frameworks and protocols) that can rapidly bring together disparate datasets from a wide variety of sources, assess the data for quality, and then process, store, and share them, in near real-time ways that are informative and accessible for users. The growing field of hydroinformatics will also be critical for combining the societal issues related to water use and need with large volumes of scientific datasets to provide innovative new insights into water resources.

While it is impossible to foresee all the advances in techniques and equipment that might occur over the next 25 years, great gains in the ability to understand and predict water quantity (surface and subsurface), quality, flow directions and rates, and residence times have come from observations related to satellite-based or airborne platforms, shallow-earth geophysical techniques, miniaturization of sensors, and data acquisition in remote settings. Biogeochemical markers (e.g., viruses, genetic material) used as environmental tracers and environmental DNA (eDNA) are poised to change the landscape of understanding environmental dynamics, including water resources. High throughput genetic sequencing of eDNA samples (e.g., application of metagenomics methods) could revolutionize the detection of pathogens and invasive species and provide important insights into aquatic ecosystem health and the cumulative impacts of multiple stressors. As new technologies gain hold or become established, there will be opportunities for greater analytical precision, accuracy, and lower costs for almost all laboratory methodologies. Real-time data processing, real-time links among data sources (e.g., between satellite observations and land-based sensors) and better analysis and visualization capabilities will increase the value of each sample collected.

Sensors for making ground-based observations have advanced significantly in ways that will allow high-density sensing in the future. These include applications such as the use of ultrasound to determine river stage, radar for measuring stream velocity, and the application of autonomous vehicles (both airborne and ground-based) as platforms for lidar and other remote-sensing applications. Distributed temperature sensing allows measurements to be made over time and space in streams and aquifers (in wells), which can also be used to indirectly measure soil moisture. Improvements are also likely in the quality and resolution of real-time precipitation measurements at locally relevant scales using radar and other remote-sensing tools. Snowpack measurement can be conducted using sensors that are able to determine snow depth, density, grain size, and albedo. Geophysical tools currently in use and in development (e.g., ground-penetrating radar, passive seismic, magnetic resonance imaging, optical and acoustic borehole imaging) can acquire valuable information about the subsurface including the presence, general composition (i.e., saline versus fresh), and flow of water. There are likely to be leaps in the application of artificial intelligence approaches to maximize autonomous, decentralized systems such as sensor networks.

Chemical measurements by deployable sensors are currently limited to only a basic set of water quality parameters (e.g., temperature, pH, dissolved oxygen). Probes to measure nitrate have been in existence for some time but remain relatively expensive to deploy and maintain. Commonly used water-quality probes require frequent field maintenance, which substantially adds to their costs (Wagner et al., 2006). Sensors that measure light absorbance can indirectly measure other water quality parameters, such as dissolved organic carbon and algae (Wymore et al., 2018). There have been promising developments in sensors that can measure other chemical species by voltammetry and microfluidic lab-on-a-chip technologies (Buffle and Tercier-Waeber, 2005; Cogan et al., 2015; Barton et al., 2016; ter Schiphorst et al., 2018). Other advances, including the miniaturization of instruments such as mass spectrometers, could make them field-deployable over the next 25 years (Snyder et al., 2016). However, issues regarding powering and hardening these sensors have been challenging.

The use of space-based Earth observation platforms supported by the National Aeronautics and Space Administration (NASA), NOAA, USGS, and international agencies have dramatically changed observations of the water cycle (NASEM, 2018a). Current missions that are sensing critical water parameters include the follow-on missions of the Gravity Recovery and Climate Experiment (GRACE-FO),[1] the U.S. Soil Moisture Active Passive (SMAP),[2] and the Global Precipitation Measurement (GPM)[3] satellites. The Surface Water and Ocean Topography

---

[1] See https://gracefo.jpl.nasa.gov; accessed September 4, 2018.
[2] See https://smap.jpl.nasa.gov; accessed September 4, 2018.
[3] See https://pmm.nasa.gov/GPM and https://svs.gsfc.nasa.gov/Gallery/GPM.html; accessed September 4, 2018.

(SWOT)[4] Mission to survey the topography of the Earth's oceans and terrestrial surface waters is expected to launch in 2021. The Moderate Resolution Imaging Spectroradiometer (MODIS)[5] and the Visible Infrared Imaging Radiometer Suite (VIIRS)[6] can measure snow-covered area, snow grain size, and snow albedo. Passive microwave sensors can estimate snow water equivalent over relatively flat, treeless regions, although global space-based measurement of snow water equivalent remains elusive. The application of space-based observations will continue with the advanced sensors developed and launched by NASA and international partners, as well as rapid deployment of large numbers of private-sector-funded satellite missions.

PRIORITY RESEARCH QUESTIONS

Given the water science and resources challenges and emerging technologies described above, the committee identified 10 science questions that, if addressed, would make the most significant contributions to respond to these and other challenges in the future. The questions below are not presented in any order of priority, as each is of critical importance for science and society. Although USGS could potentially contribute to advancing any of these questions, the committee further refined this set of questions in Chapter 3 to a smaller set representing those that would have the highest potential to advance USGS strategic science and other government priorities.

1. What is the quality and quantity of atmospheric, surface, and subsurface water, and how do these vary spatially and temporally?

Measuring water quantity is fundamental to the management of water resources. Understanding the amount and reliability of water sources is also key to water treatment and energy production and to industries that depend on water to produce their goods. As noted by Vogel et al. (2015), traditional approaches to water resources planning have centered on water quantity, while water quality assessments and the effects of human activity over time are assessed independently. There is growing awareness of the need to consider integrated water quantity and quality from a multidisciplinary perspective, including coupled interactions and human influences on both (Tundisi et al., 2015). Integrated understanding will become more pressing in the coming decades as water security issues become even more urgent. Water stocks, fluxes, and water quality parameters (including a range of natural chemicals, the contaminants introduced by human activities, and the water temperature of streams, rivers, and lakes) need to be measured, analyzed, and modeled. However, new technologies and methods used to measure water quantity and quality need to be fully validated before these data can be used in an interpretative manner.

Groundwater is increasingly being relied on for drinking water, agriculture, and industrial and energy production (e.g., Alley et al., 1999) and integrated studies will increasingly be desired. For example, understanding interactions between surface water and groundwater over time has grown in importance as water withdrawals from both surface and subsurface sources have increased. Because this interface is a highly reactive biogeochemical zone, it influences important functions such as the processing of major elements (e.g., carbon, nitrogen, phosphorous) and the attenuation of organic contaminants (Berner, 2003; Zeng et al., 2012; Schlesinger and Bernhardt,

[4] See https://swot.jpl.nasa.gov; accessed September 4, 2018.
[5] See https://modis.gsfc.nasa.gov; accessed September 4, 2018.
[6] See https://jointmission.gsfc.nasa.gov/viirs.html; accessed September 4, 2018.

2013). Coordinated programs to monitor, assess, and model the individual and joint effects of changes in the use of surface and subsurface waters and of the introduction of contaminants to these waters will continue to be essential. However, making improvements in all aspects of the programs as technologies advance in the coming decades will be a major challenge.

2. How do human activities affect water quantity and quality?

Many human activities affect the quantity of water available over time and space (Khatri and Tyagi, 2014). Effects of water use range in scale from very large—such as the major water diversions associated with the Colorado River Aqueduct or the Central Arizona Project (Zuniga, 2000) that bring water to arid regions of the country—to much smaller and less obvious transfers, such as water lost from leaking infrastructure (e.g., irrigation canals, water mains, and sewers). Human influences can also affect water quantity issues such as flood risk. Urbanization and agricultural land use can enhance rapid runoff from storms and rapidly channel stormwater to streams and rivers. Flood protection works can remove natural attenuation processes, increase flood risk downstream, and increase floodplain inundation levels (Wheater, 2006).

In addition to knowing the volumes available in surface water and groundwater and the flows within and between them, a critical science need is to learn how human activities affect these sources and sinks so that future impacts can be anticipated. Threats to water quantity are regional in nature and typically occur in areas that are both arid and population-dense and in agricultural regions that are heavily reliant on groundwater for irrigation (MacDonald, 2010). Additionally, many regions rely on sufficient winter snowpack in mountainous regions to deliver water throughout the rest of the year and to recharge deep aquifers (Barnett et al., 2005; Mankin et al., 2015); yet, snowpacks are continuing to decline (Allchin and Déry, 2017; Mote et al., 2018). Even humid regions with normally abundant resources are still susceptible to sustained drought and increased demand (e.g., the Delaware River Basin[7] or New York City [NASEM, 2018b]).

Urban land uses can affect water quality by increasing non-point storm water runoff and point sources of wastewater effluent (NRC, 2009); degrade groundwater quantity and quality through excessive drawdown, induced infiltration, reduced recharge, and multiple contaminant sources; and mobilize sediment. The expansion and intensification of agricultural land use has negatively influenced water quality at local, regional (Hansen et al., 2018), and continental scales (Diaz and Rosenberg, 2008), and also reduced the availability of water. Efforts in the United States to remove low-head dams and to return streams to their natural flows could mobilize stored sediments. The effect of these sediments to downstream environments could be deleterious to benthic ecosystems (e.g., Mbaka and Mwaniki, 2017), but the limited evidence to date show little impact with respect to legacy organic contaminants (Cantwell et al., 2014). Providing new data and science to address these issues is a critical need, given the increasing urbanization of the world and the need to produce more food as the global population expands.

Water is also used to transport human and industrial waste and is an essential component of numerous industrial processes (Peters and Meybeck, 2009). Produced and flowback water as byproducts of unconventional hydrocarbon development have become more prevalent over the past decade, raising water quality and quantity concerns (Vidic et al., 2013; NASEM, 2017). Excess nitrogen, phosphorus, and pesticides from agricultural runoff, organic solvents that contaminate groundwater, microbial contaminants such as *E. coli*, per- and poly-fluoroalkyl substances (PFAS), and thermal pollution from power plants, municipalities, and reservoir releases all affect water quality in freshwater systems across the nation.

[7] *New Jersey v. New York, 347 U.S. 995* (1954).

By increasing the export of dissolved nutrients downstream, land uses that disturb soils can fuel harmful algal blooms with cascading implications on environmental and human health (Rabalais et al., 2002, Kovacic et al., 2006). Harmful algal blooms threaten both potable water supplies and aquatic ecosystems alike (NRC, 2011), yet the ability to predict their extent and duration remains uncertain. Changing land use also affects large-scale hydrological cycle functions. Changing urban and rural landscapes, including irrigated agriculture, alter the evaporation feedbacks from land to atmosphere and have the potential to influence long-term propagation of atmospheric moisture and storms (Vörösmarty et al., 2004; Sterling et al., 2013).

Emerging contaminants (e.g., viruses, pharmaceuticals, new pesticides, personal care products, estrogenic compounds, nanomaterials) represent an unquantified potential threat to water quality and public health. Much remains unknown about the fate and transport of these contaminants (NRC, 2001, 2013). Research to minimize or mitigate negative effects of emerging contaminants on both water quantity and quality is critically needed (Rosi-Marshall et al., 2014), as the fate and ecosystem consequences of these compounds remain understudied (Boxall et al., 2012; Rosi-Marshall et al., 2013).

3. How can water accounting be done more effectively and comprehensively to provide data on water availability and use?

Accurately and completely accounting for water—understanding how much water is available, how it changes throughout the year, and how it is allocated—is critical for effective water management. However, current data-collection programs, including both measurement methods and the resulting data, are not sufficient to allow for the comprehensive accounting of water use and availability (Cooley et al., 2013). For example, in the United States, current water-accounting reports generally quantify only water withdrawals and do not distinguish between water that is returned to the hydrologic system or is used for consumption (Kenny et al., 2009). In the United States, USGS has made efforts to quantify some of these water uses, including surface water and groundwater use and trends in water use from 1950 to the present.[8] Many regions in the world, however, completely lack basic water-use data. Even when data are collected, availability tends to be limited and data quality may be questionable. Establishing consistent efforts for the collection, compilation, analysis, and reporting of comprehensive water-use data is needed to allow effective management of resources and avoid water catastrophes. Data from all countries will be necessary as global interconnections in water resources become ever more prominent.

Countries across the world need to improve water accounting (Gleick, 2003a). In the United States, for example, while there are direct measurements of domestic water withdrawals at the local and state levels, the amount and type of data gathered is generally dependent on need (Dieter et al., 2018). This is particularly true in many rural areas or areas where there is currently an adequate water supply to meet all existing needs including human consumption, irrigation, and power generation (Dieter et al., 2018). In areas where demands are high and water resources are limited, water-use data are generally acquired at or near the end use (e.g., household or industry delivery point) (Maier et al., 2016; Siegrist, 2017). Because “consumptive use” (defined as withdrawn water that is no longer available for immediate use) is not generally quantified, it is difficult to assess how these losses affect existing stocks, especially in areas experiencing water insecurity. Finally, no standard protocol exists to delineate between direct (e.g., bathing, drinking, agriculture) and indirect water use (e.g., used to produce goods, virtual water). Indirect water use

[8] See https://water.usgs.gov/watuse; accessed September 4, 2018.

can only be estimated, as there is no direct means to measure these stocks and these models are reliant on USGS water-use reports (Blackhurst et al., 2010).

The procurement of adequate data is key to effective accounting systems. Data are needed on national water use, streamflow, groundwater, water quality, and ecosystem needs in order to accurately account for water resources.

4. How does changing climate affect water quality, quantity, and reliability, as well as water-related hazards and extreme events?

Climate change is intensifying natural perturbations in the water cycle, as warmer temperatures increase evaporation, precipitation, and the water-vapor holding capacity of the atmosphere (Giorgi et al., 2011; Trenberth, 2011). When storms occur under such conditions, they can be more intense and lead to floods; while during hot, dry seasons, these same effects amplify drying of the land surface and contribute to droughts. Under current rates of carbon dioxide forcing, average annual U.S. temperatures are projected to warm by 6°F to 7°F over the next 50 years, with disproportionate warming in mountain regions (Pepin et al., 2015). Glacier retreat and reduced snowpack with earlier snowmelt will change the magnitude and timing of mountain river flows. In northern regions, permafrost thaw will change landscapes and hydrological connectivity, while earlier river ice breakup will change flood risk. More generally, the change to more intense precipitation and faster runoff will likely reduce groundwater recharge and surface-water base flows and climate-driven changes to terrestrial ecosystems, including carbon fertilization and changing fire regimes, will further modify hydrological response.

Water quality is also being altered by climate change. Higher temperatures lead to warmer water in streams and rivers, often negatively affecting cold-water fisheries, facilitating the success of invasive species (e.g., sea lamprey in the Great Lakes), and potentially exacerbating the effects of land-use change (e.g., deforestation) or industrial activities (e.g., water discharges from thermal power plants). Intense rain events, especially those following severe wildfires, increase erosion and sediment transport, which in turn mobilize contaminants. Warmer summers exacerbate harmful algal blooms (including cyanobacteria blooms) in lakes as toxic algae proliferate in warmer waters (Chapra et al., 2017). Rising sea levels can lead to saltwater intrusion into coastal aquifers (Green et al., 2011). Changing water quantity and degrading water quality are already presenting severe challenges to water resources management and are anticipated to accelerate as climate continues to change. Changes in the water cycle in future climate scenarios will not affect all parts of the world in the same way and could have significant and different impacts on a regional scale. New science is needed not only to project expected changes in water resources in the future but also to quantify, analyze, and explain the uncertainty surrounding future projections.

There is a need to understand the likely effects of climate change on extreme events. While enhanced resolution of climate models will improve the explicit representation of precipitation (Rasmussen et al., 2011), it is also likely that predictive uncertainty associated with scenarios of future climate and their impacts on regional hydrological systems will remain high (Trenberth, 2010). Particular challenges arise for northern environments, where the hydrology is dependent on cold-region processes of snow, ice, and frozen soils and where these regions are rapidly warming with potentially large feedback effects (DeBeer et al., 2016).

Infrastructure design and risk-management practices in the United States and many other countries are based on the assumption of climate and catchment stability (Milly et al., 2008). Design methods for water infrastructure are based on observed flow and precipitation records, which are typically very limited in record length in comparison with the frequencies of extreme events that are of concern (Galloway, 2011). A new paradigm is needed to guide new infrastructure design and manage the increased risks associated with socioeconomic development and accelerating environmental change (Milly et al., 2008). Furthermore, given the inherent uncertainties associated with projections of future climate and land-use impacts on the hydrologic cycle, there is a need to develop a framework for decision-making under uncertainty (Lempert and Schlesinger, 2000; Lempert et al., 2003; Wheater and Gober, 2015).

5. How can long-term water-related risk management be improved?

A 2001 National Research Council report identified grand challenges for environmental sciences (NRC, 2001). One of the challenges was "to predict changes in freshwater resources and the environment caused by floods, droughts, sedimentation, and contamination in a context of growing demand on water resources" (NRC, 2001, p. 31). Given the apparent continuing escalation in water-related disasters (see Box 2.2), this remains an important challenge for water science in the future. The report noted the following:

> *In meeting this challenge, science would draw on new high-resolution atmospheric, surface, and subsurface data obtained as a result of rapid advances in remote sensing and geophysical technology. Multidisciplinary collaboration, field measurements and experiments, and data integration would enable the development of a new body of hydrologic science, linking traditional hydrology, geomorphology, and aquatic/riparian ecology.* (NRC, 2001, p. 33)

All of these elements—new data, new integration, new science—will continue to grow apace in the future. It is imperative to continue advances in the ability to make useful multi-decade forecasts that can enable informed management of future risks to water supplies, water quality, and risks from floods and droughts.

Risks from land and water management are often multifaceted, affecting water flows, water quality, and ecosystem health. In addition, vulnerability to hydrological events is driven by societal policy, not simply the physical system. For example, human exposure to risk may be affected by choices such as installing engineering infrastructure for hazard mitigation (e.g., seawalls, levees), providing flood insurance in flood-prone areas (which may encourage people to live in areas at risk of more severe events [Gober and Wheater, 2015]), or using nature-based or green approaches to reduce the risk of flooding (Zimmermann et al., 2016). Improving the scientific understanding of these changes will be driven by more effective integration of physical sciences, social sciences, and engineering. Projections of future risks, however, are likely to continue to be associated with large uncertainty, especially when dealing with the human system. Interdisciplinary, integrated models will be needed to understand and predict the influence of environmental and societal change, as will tools that support decision-making under uncertainty, including vulnerability assessment, robust decision-making, and adaptive management.

6. How does the hydrologic cycle respond to changes in the atmosphere, the lithosphere, and the biosphere through Earth's history and in the near future? And how do the hydrologic responses feed back to and hence accelerate or dampen the initial changes in the atmosphere, the lithosphere, and the biosphere?

The flow paths and residence times of water (and the resulting water-rock contact time) in the shallow subsurface are highly sensitive to climate and topography, but they also regulate climate through weathering and the long-term carbon cycle and regulate topography through weathering and erosion (Maher and Chamberlin, 2014). Water availability drives plant evolution and adaptation and hence ecosystem structures and their functioning (Stebbins, 1952; Axelrod, 1972); and once established, ecosystems alter the water cycle through deep roots, transpiration, and precipitation recycling (Boyce and Lee, 2017) and the carbon cycle through sequestration in the soil (Shevliakova, 2017) and organic carbon burial (Berner, 2003).

Over shorter time scales, the water cycle regulates the Earth system through its fundamental role in land-based ecosystem structure and productivity. In the coming decades and centuries, the ability to predict the future climate trajectory rests on the ability to predict the response of land ecosystems to carbon dioxide fertilization and warmer temperatures, which is likely to enhance ecosystem productivity (Bonan and Doney, 2018). Many ecosystems, however, are currently under water stress, and others are predicted to experience increasing water stress. How water availability will shift in space and time in the near future, and how these shifts will enhance or reduce an ecosystem's capacity for carbon uptake and climate mitigation, are key questions to be answered. Given the short length of records from historical observations, much information can be gained from analysis of paleo records including tree rings, sediment cores, ice cores, and pollen studies, among others (NRC, 2007).

7. How can short-term forecasting for climate, hydrology, water quality, and associated social systems be improved?

Short-term hydrological forecasting (defined as forecasts over time spans of a few hours to a few weeks) is critical to society, providing immediate predictions of extreme, high-risk hydrologic events such as floods, as well as informing management and infrastructure decisions related to droughts, river flows, groundwater levels, and water management. Such short-term forecasting uses hydrologic models, which can assimilate current observations in real time (e.g., precipitation, river levels, snow water equivalent, groundwater levels, water quality, water use) and make appropriate allowance for the loss of such information in extreme events (Young, 2002; Cloke and Pappenberger, 2009). In the future, developments in the availability of spatial data can be expected to improve current forecast reliability for river flows and lake and reservoir levels, although these ultimately depend on the accuracy of meteorological forecasts, which are high for short-term forecasts but degrade for seasonal forecasts. In the United States, a new national weather forecasting model is being implemented (Adams, 2016) to augment existing National Weather Service capability (see Box 2.1). There is significant further potential for delivery of improved forecasting, for example of floodplain water levels, urban flooding, and high groundwater conditions. Short-term forecasts that could warn of floods at any location, including the identification of the potential for failure of flood-defense infrastructure, would be a major advance. Global flood and drought warning products are currently being refined (e.g., Alfieri et al., 2013; Sheffield et al., 2014) and will be enhanced as global data products improve. The scope of water-related hazard warning systems can be expected to expand to include short-term (i.e., hours to days) threats from water quality (e.g., travel time of accidental pollution, warning of harmful algal blooms and seasonal forecasts of groundwater levels).

8. How do institutions and governance and institutional resilience impact the quantity and quality of water?

Diverse institutions play roles in the management and regulation of water supply, use, quality, and infrastructure, in the context of societal values and preferences. Whether formal or informal, institutions encompass property rights, markets, regulations, policies, and socio-cultural norms (Jaeger, 2015). They can function at the local level, such as municipal water pricing and conservation measures; at the state level, such as the doctrine of prior appropriation with water rights; and at the federal level, with implementation of regulatory environmental flows for endangered species. Societies develop infrastructure (e.g., dams, canals, pipelines, wells, sewers, treatment plants, reservoirs) to store, manage, deliver, and treat water for human needs.

Institutional resilience (the ability of an institution to adapt successfully to perturbations) is a concept that has been used to describe the ability of water decision-making and management bodies to create flexible solutions to new water resources challenges. In contrast, institutional failures can have devastating impacts on water resources. Instances of lead contamination (e.g., Washington, DC [e.g., Renner, 2004] or Flint, Michigan [e.g., Campbell et al., 2016; Chavez et al., 2017]) demonstrate failures in water-related decision-making. In another example, thousands of gallons of a chemical used to remove impurities from coal spilled into West Virginia's Elk River in 2014, contaminating drinking water in Charleston, West Virginia, and several municipalities downstream. Institutional failures, both before the spill and during its response, contributed to the disaster (Lukacs et al., 2017). In cases such as the Elk River spill, stronger institutional resilience could lead to more rapid and coordinated efforts by a variety of entities, including federal agencies such as USGS WMA, to characterize and treat water-related contaminants (Whelton et al., 2015).

The challenges of managing water resources in the future are daunting. New approaches that do not simply focus on strictly technical and single-objective solutions will need to be developed. For example, adaptive governance, which explicitly integrates human dimensions and institutional arrangements to develop management goals and plans for achieving those goals, could be better integrated into the decision-making process (Akamani, 2016). To allow for wise use of water resources, the development of management approaches that are practical and flexible in the face of deep uncertainty are needed.

9. How can understanding of the connections between water-related hazards and human health be improved?

Human health and well-being can be affected by water-related hazards in diverse ways (Yusa et al., 2015), including physical injury or death, mental distress, and exposure to pollution and diseases. Floods, for example, can be a direct threat to life and property and can cause stress and consequent health responses. Hurricane Maria, for example, is estimated to be responsible for more than 2,975 deaths in Puerto Rico (Milken Institute School of Public Health, 2018) and is expected to cost at least $139 billion to rebuild property, the energy grid, and the water system, among others.[9]

In addition to loss of life and property, floods are commonly accompanied by contamination from human sewage and have been linked to waterborne disease clusters (Epstein, 2005; McMichael, 2006). As demonstrated by Hurricane Harvey in Houston, Texas, floods may create pollution hazards through inundation of existing or former industrial sites or can mobilize

[9] See https://www.npr.org/2018/08/09/637230089/puerto-rico-estimates-it-will-cost-139-billion-to-fully-recover-from-hurricane-m; accessed September 4, 2018.

river sediments that contain legacy contaminants from mining or mineral and chemical processing (EPA, 2017). Droughts can affect respiratory and mental health, infectious diseases (whether through water, food, or vectors), and illnesses related to toxin exposures, as well as food and water security (Yusa et al., 2015). Water quality may directly affect health through consumption of unsafe drinking water. For example, dissolved organic carbon, when subject to chlorination, can lead to carcinogenic disinfection byproducts (Pressman et al., 2010).

Substances in groundwater that affect human health and the health of ecosystems originate from a variety of sources (e.g., Moody, 1990). Naturally occurring elements such as arsenic and uranium can enter groundwater at unacceptable levels through geochemical processes (Nordstrom, 2002; Orloff et al., 2004). Elevated levels of nitrates and other nutrients in groundwater is a significant problem in many shallow aquifers (Rivett et al., 2008), and contamination by persistent manmade chemicals such as chlorinated solvents (Moran et al., 2007) is a nationwide concern. In agricultural areas, pesticides are ubiquitous in surface waters and groundwater used as drinking sources (Kolpin et al., 2002; Gilliom, 2007; Moschet et al., 2014). Harmful algal blooms can sicken humans who ingest contaminated seafood and can have long-term health effects including liver disease, cardiovascular disease, developmental defects, and neurobehavioral illness (Paerl and Otten, 2013; Malham et al., 2014; Campos et al., 2015; NSTC, 2016). In addition, recreational waters in close proximity to urban and agricultural areas could see increases in human exposure to pathogens (Soller et al., 2010).

Human health connections to water are multifaceted. Understanding these connections entails data assembly and analysis from sectors that are not typically seen as connected—meteorological forecasting, disease vector mechanisms, pollution control, disaster management, and water supply, among others. Coordination of the required interdisciplinary research in itself represents a formidable challenge, particularly as the impacts of climate change and land-use changes related to a growing global population occur in this century (Pandve, 2010; Khedun and Singh, 2013).

10. How can competing uses for water resources be managed and maintained to sustain healthy communities and ecosystems in a changing world?

At the heart of water resources challenges is the conflict among competing water uses. One of the many such conflicts is between human societies and ecosystems. For example, widespread groundwater depletion for irrigation poses threats to groundwater-fed streams, lakes, and wetlands, as well as their dependent aquatic ecosystems (Winter et al., 1998). The alteration of natural flows disrupts aquatic ecosystems, and the risk of ecological change increases with the magnitude of flow alteration (Poff and Zimmerman, 2010). Water is also necessary to maintain ecosystem function in terrestrial ecosystems such as forests, wetlands, and prairies, especially under changing water regimes (Baron et al., 2002; Grant et al., 2013). Riparian floodplain forests, along river and stream corridors, rely on seasonal inundation to maintain their structure and function and in turn provide ecosystem services to adjacent freshwaters through shading, bank stability, carbon inputs, and nutrient retention (Richardson et al., 2010). From uplands to lowlands, water science challenges include measuring, monitoring, and understanding water quantity and quality needed to maintain the structure and function of ecosystems and maintaining ecosystem services in the face of environmental change.

An additional set of conflicts arises among competing human water uses, such as water resource allocation for drinking water supply, industry, and agriculture, as well as the management of reservoirs for hydropower, water supply, and flood protection. Conflicts arise at multiple scales, often involve many actors, and may cross jurisdictional boundaries, including among states or international governments. The food-energy-water nexus was conceived to help clarify the interdependence of and tradeoffs between some of these critical components (Beddington, 2009; Perrone and Hornberger, 2014; Scanlon et al., 2017). Increasing pressures of climate change, population growth, and technological shifts pose sustainability and management challenges to the food-energy-water nexus. In particular, as noted by Vaux (2012, p. 145), "the allocation of water between agriculture and the environment is a significant issue globally, nationally and locally and can no longer be taken for granted." To better understand the complex tradeoffs in the food-energy-water nexus, USGS will need to bring together a broad spectrum of disciplines to provide data, information, tools, and the expert knowledge necessary to manage competing uses of water. A holistic approach will be needed to address the technological and non-technological issues to help decision makers prioritize their efforts, such as engineering and technological innovations for water allocation and resource management, as well as social issues such as environmental justice and affordable access to high-quality water. There is increasing recognition that the social process of stakeholder engagement with water science is as least as important as the knowledge yielded by the science (Wheater and Gober, 2015).

3
Priority Questions and Recommendations

In Chapter 2, the committee identified a broad suite of water science and resources challenges and questions that are key for making significant advancements to address national and global water issues. These 10 questions are highly important and addressing them would be valuable for the nation. A subset of these questions, however, has been determined by the committee to have the highest potential not only to address the critical water science and resources challenges but also to advance the U.S. Geological Survey's (USGS's) strategic science priorities and those of its partners (see Statement of Task 3 and Box 1.1).

To identify which questions among the 10 described in Chapter 2 would best achieve these goals, the committee developed a rubric to highlight the questions with the (1) highest scientific importance, (2) relevance to pressing societal needs, (3) alignment with USGS strategic directions, and (4) opportunities for collaborations among the Water Mission Area (WMA) and its partners, including other USGS mission areas (see Appendix A for a discussion of other mission areas), other federal agencies, and state and local partners (see Appendix D). When the rubric was applied to the questions in Chapter 2, five questions arose that met these qualifications to the highest degree. Although the committee offers these five questions as the top priorities, it encourages USGS to address the other questions as resources permit.

In addition, WMA asked the committee to consider tools and approaches WMA may employ for observing, understanding, predicting, and delivering water science. These technological innovations—sensors, new modeling approaches, data visualization, and citizen science—are discussed below, as they set the context for how to address these high-priority questions.

TECHNOLOGICAL INNOVATIONS

Sensors

New space- and ground-based sensors have the ability to advance observations and analysis of water resources. Space-based sensors for global-scale observations of water stocks have made great advances (Lettenmaier et al., 2015), but technical challenges exist with respect to measuring and monitoring water quality. Integrated, multiagency initiatives (e.g., 3D-Nation[1]) that use tools such as high-resolution lidar are expected to provide seamless topographic and bathymetric elevation coverage across the nation. Drone-based platforms will advance monitoring of water

[1] See https://my.usgs.gov/confluence/display/3DNationStudy/3D+Nation+Requirements+and+Benefits+Study; accessed September 17, 2018.

quantity, quality, and ecosystem health. In the near term, nutrient monitoring using probes are likely to remain expensive, and the reliability of electrochemical electrodes and "lab-on-a-chip" sensors are not yet known in long-term deployments (Banna et al., 2014). In the near future, the application of sensors capable of continuously detecting and measuring organic (e.g., pesticides, emerging contaminants) and inorganic micropollutants (e.g., certain metals) remains technologically infeasible at environmentally relevant levels. Microsensors, however, remain an area of research and development that shows great promise, and the technology will continue to develop, improve, and become more affordable. The miniaturization of mass spectrometers may enable field deployments that can be tailored to detect specific contaminants at environmental levels (e.g., Snyder et al., 2015), while developments in environmental DNA (eDNA) analysis may revolutionize monitoring of ecosystem health and resilience.

Big Data and New Modeling Approaches

While the recent past has seen unprecedented growth in computing capacity, enabling models with high resolution and process fidelity at all scales, the future will depend on the treatment of extremely large-volume data sets (i.e., "big data"). Data from multiple sources and locations, including both biophysical and human-system information, will be assimilated into models on a near real-time basis; and models developed by experts in individual domains will be integrated, requiring attention to common data protocols and interoperability—the ability for different data systems and software to communicate (Kingdon et al., 2014). Technologies such as cloud computing (discussed in the next section) and the "Internet of Things" will continue to advance and will need to be incorporated as part of water modeling platforms (Granell et al., 2016). The field of data analytics, which uses algorithms to find correlations not previously considered within datasets, will also be a critical area of future improvement.

These developments will support improved scientific understanding, development of improved water models, and interdisciplinary model integration. Remotely sensed information on surface-water levels, soil moisture, vegetation status, snow and ice, and groundwater storage could provide new data products that will enhance model capability and improve both short-term forecasts and longer-term projections of change. Models with national coverage, running at multiple spatial and temporal scales that integrate weather, surface water, and groundwater hydrology might provide the framework for delivery of these and other new data products. Such models will allow cross-site interpolation and synthesis to provide hydrologic information at any desired location and scale. These models will also support integration of a suite of other components essential to the USGS water missions, such as human impacts, climate change, ecosystems, water quality, and human health (Patterson et al., 2017).

Improved coupled modeling of the natural-human water system will need to include infrastructure, operational management, and human values and preferences. Models that incorporate decision-support systems will be able to assist natural resources managers and policymakers to inform management and policy decisions, especially if they are user driven, co-developed, and "fit-for-purpose." Projections of future human impacts and risk are inevitably associated with large uncertainties; therefore, there is a need to develop a framework for decision-making under uncertainty.

Cloud Computing and Data Visualization

There is a strong need to improve access to water resources data, computational tools, and presentation. In the near future, such access will largely take place through mobile devices, social media, Web-based tools, and intuitive visualizations, but opportunities also exist to employ augmented and virtual reality. Options already exist to deliver time-sensitive, broadly useful data through social media, such as the Twitter feed on USGS's Texas Water Dashboard that shows streamgages in flood stage[2] and the USGS FloodWatch app for mobile devices. These types of outreach could be greatly expanded.

Web-based cloud services, which offer the multiple advantages of ready public access to big data and open-source tools to easily manipulate and visualize data, avoid the need for major investment in technological resources, expertise, and proprietary software. Such an approach enhances opportunities for broader public engagement and actionable science. USGS is currently in the early phase of developing cloud-computing services through its Cloud Hosting Solutions enterprise. At the present time, the USGS cloud enterprise is intended for USGS Water Science Centers and mission programs.[3] Future efforts will need to expand in order to facilitate public access to cloud solutions. Cloud-based decision-support tools provided in easily accessible formats could be used to allow interested citizens and professional managers to investigate the consequences of different scenarios (e.g., flooding) within their areas of concern.

Data Outsourcing

Historically, USGS scientists and technicians were among the only groups in the nation with the training and qualifications to collect consistent, accurate, and unbiased water resources data, and USGS water programs were well supported in federal budgets. Now, more than half of WMA funding comes directly from state and local sources (see Appendix A for more discussion), and many state, local, and academic institutions have developed water resources research and monitoring capabilities that rival or even surpass the resources available to USGS personnel.

Although there are a wide variety and quantity of data currently being collected by agencies outside USGS, barriers exist to integrating these data into national databases due to long-established USGS "gold standard" protocols (Crilley, personal communication[4]). WMA has not only recognized these issues, but has begun to respond by providing cost-sharing to local stakeholders and establishing uniform data protocols through programs such as the National Ground-Water Monitoring Network and the National Water-Use Science Project (see Appendix A). Such data outsourcing, for which USGS serves as a national data repository and manager, rather than the main data collector, is likely to continue and expand in the future.

Citizen Science

The past decade has seen a huge growth in citizen science, when the public engages in data collection and analysis using sensors, computers, and mobile devices. These crowdsourcing science examples are an outgrowth of established citizen science programs, such as the Audubon

[2] See https://txpub.usgs.gov/txwaterdashboard; accessed September 17, 2018.
[3] See https://my.usgs.gov/confluence/pages/viewpage.action?pageId=568560396; accessed September 17, 2018.
[4] Communication during committee's open session in San Diego, CA on November 30, 2017, with Dianna Crilley, Associate Director for Data, USGS California Water Science Center.

Bird Surveys, with more recent versions examining where earthquakes were felt,[5] collecting information about marine debris,[6] measuring precipitation,[7] analyzing data from the Hubble Space Telescope,[8] and exploring underwater imagery.[9] Nascent efforts to use citizen science to improve streamflow data already are underway and the ability to make ever more sophisticated measurements is very likely to proceed apace over the next 25 years. In partnership with USGS, CrowdHydrology[10] uses crowdsourced observations of stage-height data at numerous sites in 15 states, while Stream Tracker, a National Aeronautics and Space Administration (NASA)-funded citizen science project, documents intermittent stream flow.[11] The National Water Quality Monitoring Council, also in partnership with USGS, provides information to organizations interested in establishing citizen science monitoring programs.[12]

The opportunity for citizen scientists to fill data gaps and supplement existing data networks through collection of basic water-quality measurements or water sampling for later analysis will continue to grow. Such citizen science data could provide crucial information to feed into water-quality databases and could be used to corroborate predictive water-quality models. The challenge, however, is how to make sure that the data quality is adequately understood, verified, and documented. The role for citizen analysis is likely to keep expanding in the future and change as technology evolves.

NEW APPROACHES FOR OLD PROBLEMS

As previously mentioned, critical water resource challenges for the coming decades are unlikely to fundamentally differ from existing challenges. Looking forward 25 years, disruptive changes (e.g., technological innovations mentioned above) and the continued development of physical scientists, social scientists, and engineers who can utilize these advances and collaborate with one another across disciplines will allow for novel approaches that can transform WMA. The priority questions discussed below, and their attendant recommendations, should be read in this context. Many of the topics discussed in the next section are already part of ongoing USGS programs. Nevertheless, the committee believes it is worth noting that there is a clear need for a forward-looking USGS to adopt a more flexible and nimble strategy to enable rapid changes in data, technology, and workforce expertise.

[5] See https://earthquake.usgs.gov/data/dyfi; accessed September 17, 2018.
[6] See, for example, http://depts.washington.edu/coasst/what/vision.html; access September 17, 2018.
[7] See https://www.cocorahs.org; accessed September 17, 2018.
[8] See http://hubblesite.org/get_involved/citizen_science; accessed September 17, 2018.
[9] See, for example, https://squidle.acfr.usyd.edu.au/#; accessed September 17, 2018.
[10] See http://www.crowdhydrology.com; accessed September 17, 2018.
[11] See https://www.streamtracker.org; accessed September 17, 2018.
[12] See https://acwi.gov/monitoring/vm/resources.html; accessed September 17, 2018.

PRIORITY QUESTIONS AND RECOMMENDATIONS

1. What is the quality and quantity of atmospheric, surface, and subsurface water, and how do these vary spatially and temporally?

To effectively manage water resources and to provide clean and safe water for all, there is a critical need for reliable, comprehensive data on the quantity and quality of the nation's surface water and groundwater resources. WMA is tasked with collecting water quantity, movement, distribution, and quality data, which are archived in the National Water Information System. A central element of this program is to deliver the data that the United States needs to manage and protect surface water and groundwater resources and minimize water-related risks. WMA also plays an essential role in providing information that is of great use for other USGS mission areas, federal agencies, and state and local partners. For example, studies at USGS Northern Prairie Wildlife Research Center (within the Ecosystems Mission Area) rely on hydrologic data collected by WMA scientists, which have resulted in many successful collaborations (e.g., McKenna et al., 2017; Levy et al., 2018, and references therein; Mushet et al., 2018). The upcoming NASA Surface Water and Ocean Topography (SWOT) Mission will be dependent on USGS streamgage data, which is used to ground-truth satellite measurements and calibrate stream discharge models (Pavelsky et al., 2014; Solander et al., 2016). Collaborative efforts with the private sector may also become important.

While USGS excels in the collection of high-quality water-resources data, current needs for water data are unprecedented, and current technologies have raised the bar for water-data delivery and interpretation. Therefore, a re-evaluation of the National Water Information System's strategic goals and capabilities is needed to ensure that WMA is nimbler in response to environmental change; this includes monitoring relevant components of the hydrological cycle as well as the interactions among them. Analysis of these observations leads to operational decisions ranging from the federal to the local level, such as determining river flows or groundwater withdrawals (McNabb, 2017). However, because no set protocol exists with respect to data measurement and reporting, there are issues with interagency data sharing and cooperation; these issues could be minimized by having different agencies agree on standard formats for measuring and reporting data. The Water Quality Portal, sponsored by USGS, the U.S. Environmental Protection Agency (EPA), and the National Water Quality Monitoring Council, exemplifies cooperation among federal agencies, state agencies, and citizen groups. The panel serves data collected for many diverse purposes by more than 400 state, federal, tribal, and local agencies. Another example is the Advisory Committee on Water Information.[13] As the lead agency, USGS can advocate for uniform standards, guidelines, and procedures for the collection, analysis, management, and dissemination of water information.

With all the pressures on the water environment, USGS will need to re-evaluate its current capabilities in the context of new opportunities that may not necessarily always meet the agency's current strict guidelines with respect to data collection, data quality, and evaluation. These new platforms include big data–driven model assimilation and integration, new applications of social media, and expansion of citizen science (discussed in a previous section). Not all of these uses necessarily need the "gold standard" of data collection that USGS is known to deliver, which may provide an opportunity for USGS to assess the level of quality that could be needed for different uses (i.e., "fit-for-purpose"). Innovative approaches will expand spatial and temporal monitoring frequency and enhance the capability to deliver data that meet specific user needs. USGS could

---

[13] See https://acwi.gov/acwi_factsheet_oct_2017.pdf; accessed September 17, 2018.

also consider a training role, bringing together stakeholders to coordinate methodologies to promote data consistency across USGS scientists and stakeholder groups. USGS is a natural fit to prioritize the ever-increasing demands for all types of water quantity, quality, and use data.

Recommendation 1.1: Enhance data collection, include citizen science, and develop Web-based analytical tools.

> **To enable the nation to meet future water resources challenges, WMA should (1) strategically enhance the temporal and spatial collection of water quantity, quality, and water-use data using robust, innovative technologies to develop readily accessible "fit-for-purpose" information; (2) further infuse citizen science into USGS data-collection activities to augment traditional monitoring networks; and (3) develop innovative, intuitive Web-based data analysis and visualization tools for the nation to better understand the status and trends of its water resources.**

Recommendation 1.2: Coordinate with agencies and organizations on data delivery.

> **As part of the national effort to deliver water quantity and quality data and information, WMA should coordinate with other agencies and relevant organizations to co-develop accessible, open, and codified data formats, protocols, interoperability, and software tools. This will allow integration across data streams and encourage synthesis of multiple observations in order to detect trends, patterns, and changes in water quantity and quality.**

Venues that USGS might explore for fostering coordination of activities related to the provision of data needed to address key water resources challenges in coming decades include the Advisory Committee on Water Information, which has played a coordinating role in some instances, and the National Ground-Water Monitoring Network (see Appendix A), which leverages data from state and local cooperators and supports local data collection and open data formats.

2. How do human activities affect water quantity and quality?

Assessing the role of human activities in water quality and quantity is key to understanding and managing water now and in the future. Human-induced changes to the land and water environment include replumbing of the hydrologic cycle through water withdrawals and diversions; changes in infiltration resulting from impervious surfaces in urban areas, which influence runoff and contaminant delivery; changes in water, nutrient, and sediment delivery from agricultural land use; and alterations to water quality through the release of nutrients, pathogens, and deleterious substances to groundwater and surface water. USGS has a role to play in not only basic water monitoring, but also in assessing and predicting the role of human and natural stressors on water quality and quantity (Van Metre et al., 2017). Continuity in its surface water and groundwater quantity and quality monitoring programs will enable USGS to elucidate trends in water movement, storage, abundance, and quality as human activity continues to alter the hydrologic cycle. These programs will provide the basis for implementing the necessary modeling to project anticipated changes.

A major challenge for USGS to address this question for the entire nation will be to manage the streamgage and observation well networks so that changes from anthropogenic activity can be captured. There are opportunities for USGS to optimize its current water monitoring efforts and employ new technologies and methods to both better observe changes to water resources and fill existing data gaps. For example, the USGS National Water-Quality Assessment Program (NAWQA) has included a focus on human-impacted watersheds (NRC, 2012d). USGS also hosts the National Ground-Water Monitoring Network Data Portal, which provides access to groundwater data from multiple, distributed databases. In the future, it will be beneficial to periodically reassess and optimize monitoring locations and sampling frequencies to capture changes due to human activities.

USGS could bridge data gaps in the observation network through collaborative efforts with other federal and state agencies. For example, cooperation between USGS and the U.S. Army Corps of Engineers (USACE) occurs on a wide range of topics, from snowpack assessments to flood mitigation efforts. USGS also collaborates with several federal agencies—including EPA, the National Oceanic and Atmospheric Administration (NOAA), USACE, and the U.S. Department of Agriculture (USDA)—to monitor drought conditions in the United States. Opportunities exist where data shared between USGS and other agencies can be utilized to observe trends in human activity that could affect water resources. In addition, tools used to predict land-use change or plans for anticipated water infrastructure can be used to help guide USGS regarding new locations for additional water measurements.

USGS could provide leadership in developing predictive models to assess future water quantity and quality conditions under different land- and water-use scenarios. A regional-scale predictive model of future groundwater storage, recharge, discharge, and human withdrawals, under plausible future agricultural, conservation, and climate scenarios, can offer a forward-looking vision on the water security of the region and food security of the nation. USGS has the expertise to lead such future assessments, and through its regional Water Science Centers (e.g., Lauffenburger et al., 2018) can develop a set of predictive models for regions under future significant water sustainability stress.

USGS is also poised to contribute significantly to understanding human impacts on water quality. Past and current monitoring efforts through NAWQA were the first to detect emerging contaminants in both aquifers and surface waters (Kolpin et al., 2002), and USGS analytical capabilities make it particularly well suited to detect the effects of human activity on aquatic ecosystems. For example, feminization of male fish by estrogenic compounds was first reported by the USGS Ecosystems Mission Area (Blazer et al., 2007) and collaborations with WMA through NAWQA has detected the presence of other pharmaceuticals in fish tissue (Schultz et al., 2010). Given the critical human impacts on water resources, maintaining and strengthening collaboration between WMA and other USGS mission areas will be important, as will collaborations with local, state, federal, and transboundary agencies. USGS modeling to understand and predict stressors on water quality, such as the SPARROW (Spatially Referenced Regression On Watershed attributes) model for the Mississippi River Basin (e.g., Alexander et al., 2008; Robertson et al., 2009), will continue to play an important role in setting water policy to ensure clean water for all uses.

Recommendation 2.1: Increase focus on the relationships between human activities and water. **WMA should prioritize investigations of the relationships between human activities and changes in surface water and groundwater quantity, quality, and water-related hazards through a careful synthesis of observations and coupled natural-human systems models forced by climate and socioeconomic factors.**

3. How can water accounting be done more effectively and comprehensively to provide data on water availability and use?

USGS currently faces challenges with respect to water accounting. The SECURE Water Act of 2009 had specific mandates that included providing a more accurate assessment of U.S. water resources, determining the quantity and quality of water available for beneficial use, and identifying long-term trends in water availability. WMA produces 5-year water-use circulars[14] (e.g., Hutson et al., 2004; Kenny et al., 2009; Maupin et al., 2014; Dieter et al., 2018) that provide critical documentation in support of the SECURE Water Act of 2009 (42 U.S.C § 10361). USGS collects county-scale water withdrawal data for these summaries, organized by specific use (e.g., livestock, golf courses, aquaculture) as well as water sources (e.g., groundwater, surface water, saline sources, total).

However, USGS has not tracked consumptive use since 1995; data gaps exist within several water-use categories (e.g., industrial, livestock, mining) and withdrawals are based on estimates. In addition, the 5-year reports are often significantly delayed (e.g., the most recent 2015 data assessment was released in 2018 [Dieter et al., 2018]). The current water-use program does not appear to have a systematic approach to evaluating the accuracy of water-use data.

The current dependence on state and local partners to collect most water-use data has led to inconsistent data collection and, in some cases, to significant data gaps. Water-use reporting is mostly in response to state regulations (which vary across the nation), and USGS does not have authority to mandate the collection of these data. Some states do not collect such data, while others may not have the ability to share it with the federal government. For example, some local water users may feel that their water consumption is a proprietary issue. This does not, however, make coordination and communication between USGS, as a national reporting agency, and the states, as data collectors, any less essential.

New methods are in use or development to aid in the estimates of water withdrawals. For example, data from space-based Earth observation platforms can model water withdrawals based on land use, evapotranspiration, and precipitation (van Eekelen et al., 2015). Satellite-based measurements can be used in conjunction with water-use data to provide assessments of existing and future available water stocks (Solander et al., 2017). These new tools, in conjunction with new consumption models, can enable USGS to refine water use estimates in the future.

Understanding the extent and patterns of anthropogenic water withdrawals is critical toward assessing available and future water stocks and their impact on aquatic and watershed ecosystems (Vörösmarty et al., 2000, 2010; Gleick, 2003a,b). USGS's efforts to quantify water usage are an essential function to assess both current and future water needs for human use and ecosystem function. Integrating resources management with remote sensing is important in efforts to fill data gaps and bridge the nexus among water, energy, and food (Sanders and Masri, 2016). Understanding how humans influence the water cycle through withdrawals to support energy and food production, industrialized activities, and domestic consumption will have significant consequences with increasing population, climate change, and globalization.

When coupled with climate change effects, factors such as population dynamics, the nature of human-built water infrastructure, and decisions about water management and use will affect total water demand and availability. Improvements to current water-accounting practices will be needed to determine how much consumptive water is permanently lost to the hydrologic system for a specific region. Furthermore, withdrawal values based on estimates will need to be corroborated by other methods such as remote sensing.

[14] See https://water.usgs.gov/watuse; accessed September 17, 2018.

To better manage the nation's water resources, models that predict water usage will need to be refined in a manner that integrates "on the ground" assessments with data derived from remote sensing. A combination of improved models and better-constrained datasets could lead to policies that are better able to mitigate the impact of human water withdrawals and consumptive use on sensitive watersheds that may not be able to sustain development and growth in the future. USGS will need to collaborate closely with other federal agencies and states to collect, analyze, and integrate critical data.

Recommendation 3.1: Develop a robust water accounting system.

WMA should conduct studies to understand how to best and most efficiently execute water accounting and how to assess and present uncertainty in the reported data. Water accounting should go beyond measurement of the resource itself to consider the biophysical and societal constraints on water use and should include estimates of consumptive versus non-consumptive water use.

Recommendation 3.2: Collaborate with agencies and organizations on water-data standards and categories of use.

As part of the national effort to collect water-use data and information, WMA should collaborate with other agencies and relevant organizations to co-develop standards, protocols, and clear definitions for categories of water use, and should adhere to common format standards across states, counties, and watersheds.

4. How does changing climate affect water quality, quantity, and reliability, as well as water-related hazards and extreme events?

Natural and human-caused climate change will strongly influence the hydrologic cycle and freshwater resources (IPCC, 2013; USGCRP, 2017). Such effects can now be observed in a wide range of systems, including changing evaporative demand associated with rising temperatures, dramatic changes in snow and ice, alterations in precipitation including the frequency of extreme events, and rising sea levels (Bates et al., 2008; NRC, 2012b,c; Georgakakos et al., 2014; Haddeland et al., 2014; Jiménez Cisneros et al., 2014).

WMA has fundamentally contributed to observing changes with its extensive, long-term monitoring of the nation's surface water and groundwater quantity and quality. This long-term monitoring has provided the observational basis for scientists (including those within USGS) to detect trends in water resources and frequency of water-related hazards and to make correct attributions for these changes, and for practitioners to design infrastructures to mitigate and adapt to the change. WMA is also collaborating with other federal agencies to develop predictive models (e.g., the National Water Model; see Box 2.1) from local to national scales.

Looking ahead, USGS is well positioned to play a leadership role in monitoring, detecting, understanding, and predicting climate-driven water quantity and quality changes and delivering such knowledge to the end users and the public. WMA needs to strategically monitor indicators of water quality and quantity at locations and timescales that will most likely be affected by climate change in the coming decades and to use this information in developing and refining integrated models that can be used to project potential hydrologic impacts of a changing climate.

USGS is a leader in synthesis activities to search for patterns and trends in climate change, as well as their underlying causes. To further improve understanding in the future, WMA could recommend critical water quality and quantity indicators that need to be more closely monitored and processes that need to be represented in predictive models. The USGS Powell Center for Analysis and Synthesis[15] is well positioned to solicit and support synthesis activities that can be co-led by USGS and academic scientists.

To enable stronger predictive capabilities, WMA can continue to develop integrative models that consider surface water and groundwater processes simultaneously. Such models can treat water quantity and quality as co-evolving entities. Given the challenge of modeling large areas while maintaining sufficient detail for local decision-making, models might nest small-scale simulations in larger spatial contexts to provide meaningful information to managers from the watershed to the national level. Future modeling efforts might also integrate human and climate forcing and strategically use extensive USGS observations through parameter estimation, data assimilation and model validation and benchmarking. At the national level, WMA can collaborate with other federal agencies through projects such as the National Water Model (see Box 2.1) by contributing expertise in process representation and by providing a national hydrogeologic framework that supplies subsurface parameters such as porosity and permeability of the soils and sediments.

To deliver this information, WMA needs to advance its work on interactive visualizations that show patterns and trends of the hydrologic effects of climate and land-use change from the national to the local level.

Recommendation 4.1: Ensure that monitoring networks provide adequate information to assess changing conditions.

USGS should periodically assess the state of surface water and groundwater monitoring networks to ensure that these networks can provide data for hydrologic impact analyses as environmental conditions change due to climate, agriculture and other land uses, and urbanization.

5. How can long-term water-related risk management be improved?

Environmental change and societal decisions alter the nation's vulnerability to hydrologic risk. Hazards such as floods, droughts, and water-borne contaminants, are driven by changes in climate, land cover, hydrology, and biogeochemistry and are increasingly affected by how humans manage land-use and water resources. A need exists to improve the scientific understanding of how humans interact with the environment and how those interactions affect water resources and risks. USACE and the U.S. Bureau of Reclamation have oversight of the construction of engineered approaches to long-term hydrological risk (e.g., infrastructure such as dams and levees), the Federal Emergency Management Agency (FEMA) has oversight over response to immediate risks, and EPA regulates water quality. USGS produces the data and tools that inform the actions of those agencies, such as producing models and software for predicting surface water and groundwater flows, assessing water quality, and collecting data on and calculating recurrence statistics for extreme events. These scientific tools also assist in state and local decision-making.

Models that integrate across human and natural systems will be needed to improve the understanding and prediction of long-term, multi-decade, environmental, and societal impacts. They can also inform policy and management decisions while accounting for deep uncertainty in human decision-making. Interdisciplinary research to fully understand and predict linkages among surface water and groundwater, water quantity and quality, and natural and human systems is needed (Wheater and Gober, 2015). These models can be used to inform risk-management actions,

[15] See https://powellcenter.usgs.gov/about; accessed September 17, 2018.

such as informing communities of changing risks of floods and pollution, supporting the management of complex water resources systems, and predicting how land-use change may affect the climate and how extreme events will influence the global economy.

Given the complex interactions and feedbacks in the natural-human water system, better prediction and risk management will need both new observational data and integration of models across disciplines. Managing long-term water-related risks in the face of environmental and societal change will require improved understanding of observed historical change. Models can play a key role in the diagnosis of the complex interactions (whether societal policy, human actions, or environmental change) that underlie the past. USGS should lead an effort that develops improved process-based understanding of water and associated nutrient and contaminant movement as a function of environmental change and that quantifies outcomes at a range of spatial and temporal scales. Improving long-term water-related risk management will also require better understanding of the likely effects of climate change on extreme events (e.g., Polade et al., 2017) due to their impacts on regional hydrological systems. Models are also needed that consider both the physical system and the human-economic constraints on the system to fully understand risks of shortages in water availability.

Prediction of future hydrologic risks will be based on simulation and evaluation of potential outcomes from environmental scenarios within social and economic constraints. Building capacity for reliable long-term prediction and risk management requires developing a validated understanding of complex socio-hydrological systems, developing models to simulate these systems, and exploring a range of alternative future scenarios. The work will need to leverage new data streams and computational technologies and adapt to changes as they occur over the next several decades. USGS can lead this effort through improving the prediction of surface-water and groundwater systems and developing new capabilities for integration of models to predict the complex interactions that underlie water-related risks from future change.

Recommendation 5.1: Focus on long-term prediction and risk assessment of extreme water conditions.

> **WMA should prioritize activities that address long-term prediction and risk related to hydrologic causes such as floods, droughts, and water-borne contaminants. WMA should seek to understand how climate change, land-cover and land-use change, and other biophysical and socio-economic factors affect the nation's water resources, including water quantity and quality, extreme events, and other hydrologic hazards. USGS should further develop integrative models that can help predict future hydrologic conditions under these changing climate conditions. These activities will require integrative studies with other USGS mission areas and should include resource managers, decision makers, and social scientists.**

ADDITIONAL RECOMMENDATIONS FOR THE WATER MISSION AREA

Integrated, coupled system models are necessary to better understand the complex water systems—whether natural components, human impacts, or evolving states such as changing climate and environmental conditions. Integrated models that incorporate appropriate temporal and spatial scales will improve understanding of water quantity, water quality, and the linkages and feedbacks among hydrologic components.

Recommendation 6: Develop multiscale, integrated, dynamic models that encompass the full water cycle.

> **WMA should prioritize multiscale and integrated modeling efforts that dynamically couple above- and below-ground hydrologic stores and fluxes, water quantities and qualities, and natural and human drivers and interactions, and utilize diverse observations ranging from ground-based sensing to Earth observations from airborne and space-borne platforms.**

Given the growing importance of water resources challenges to lives and livelihoods, economic development, and environmental health, and the increasing costs of water-related disasters, there is a strong argument that water-related agencies should continue to work together, and even strengthen their ties. Opportunities exist for WMA to provide scientific support to other agencies within the U.S. Department of the Interior in areas such as potable water reuse, desalination, and water use and disposal associated with unconventional hydrocarbon extraction. The U.S. Bureau of Reclamation's WaterSMART program is a prime example of how WMA can collaborate and provide support to advance the science associated with water conservation. Collaboration has always been a strong suit of WMA; yet, it is critical to continue and expand these collaborations and partnerships as resources become more limited. One of the areas ripe for collaboration is integrated modeling—WMA could draw on the expertise of other USGS mission areas, which hold some of the core data (e.g., modern geologic maps) that are needed for such integrative efforts.

Recommendation 7: Collaborate as appropriate both within and outside of USGS, including agencies and the private sector.

> **Given that water resources challenges are inherently interdisciplinary, WMA should continue to build and maintain strong collaborations. WMA should maintain and strengthen ties with other USGS mission areas to maximize the impact of its work on observing, understanding, predicting, and delivering water data and issues. WMA should maintain and strengthen ties with other federal and state agencies, and as appropriate, international agencies (especially regarding transboundary water issues) to meet these water resources challenges. WMA should also evaluate and, where deemed advantageous, engage in private-sector collaborations to develop new data sources and platforms, and in the dissemination of data and information, models, and other products.**

In 2015, USGS produced a *Bureau Workforce Plan*, in which it outlined some broad needs for the future.

> *Moving into the future, it is paramount to maintain USGS scientific capability and reputation and provide skilled and innovative science support.… [T]here are key skill sets and capabilities that while currently found in the USGS, will be increasingly needed in the future. There will be increasing demand for multidiscipline syntheses and landscape-level science, which will require capabilities such as mapping, geospatial data integration, remote sensing, predictive modeling, scenario development, forecasting, simulation, and decision support.… The USGS will also need a workforce that can adapt to new technology*

> *and respond quickly, in both quantity and expertise, to changes in science and management priorities.* (USGS, 2015, p. 1)

Given the priority questions above, the committee emphatically endorses the aims outlined in that USGS report.

The modern WMA workforce will need to reflect the priorities of emerging and future science questions and technologies. In addition to WMA's current workforce strengths in hydrology and water science, a highly trained workforce with expertise in data and computational science (including big data, data analytics, and data delivery and visualization); modeling; remote sensing; disciplines such as climate science, hydrology, geochemistry, and ecosystem science; and interdisciplinary fields such as hydroclimatology and hydrochemistry will be needed. The future workforce will need to be nimble, inter- or multi-disciplinary, collaborative, and adaptive.

Recommendation 8: Build a workforce who are ready to take on new water challenges.

WMA should align its current and future workforce to meet critical strategic needs, specifically building capacity for improved water monitoring; coupled natural-human systems modeling; and data analysis, analytics, visualization, and delivery using reliable, accurate, robust, and innovative methods.

FINAL THOUGHTS

The committee was charged to identify the nation's highest-priority water science and resource challenges over the next 25 years. The committee is cognizant of the proverb "it is difficult to make predictions, especially about the future," but believes that there are clear trends that lend support to these views of future water challenges. The global population will grow by 2 billion by 2040 and will place additional demands on natural resources. This growth in population will be realized during a time of economic advances in the developing world, which will likely amplify demands. Global temperatures will continue to increase over the next 25 years, and climate change will continue its course. The world population living in urban areas will grow to about 60 percent by 2040. All these changes will add to the water resources challenges identified above, with concomitant needs for new data, information, analyses, and science to address the challenges.

USGS has been the premier federal agency for water resources since its establishment in 1879 and continues to be so. The committee envisions that WMA will adapt in the future to deliver the necessary data and science to enable the country to manage its water resources effectively and to deal with hazards. The five high-priority questions identified above can provide a framework to help guide the evolution of WMA, so that USGS can effectively address the water resources challenges that will face the nation over the next 25 years.

References

Adams, T. E. 2016. *Flood forecasting in the United States NOAA/National Weather Service*. Pp. 249-310 in *Flood Forecasting: A Global Perspective*, T. E. Adams and T. C. Pagano, eds. Amsterdam: Academic Press.

Akamani, K. 2016. Adaptive water governance: Integrating the human dimensions into water resource governance. *Journal of Contemporary Water Research and Education* 158(1):2-18.

Alexander, R. B., R. A. Smith, G. E. Schwarz, E. W. Boyer, J. V. Nolan, and J. W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. *Environmental Science & Technology* 42(3):822-830.

Alfieri, L., P. Burek, E. Dutra, B. Krzeminski, D. Muraro, J. Thielen, and F. Pappenberger. 2013. GloFAS—Global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences* 17(3):1161-1175.

Allaire, M., H. Wu, and U. Lall. 2018. National trends in drinking water quality violations. *Proceedings of the National Academy of Sciences of the United States of America* 115(9):2078-2083.

Allchin, M. I., and S. J. Déry. 2017. A spatio-temporal analysis of trends in Northern Hemisphere snow-cominated area and duration, 1971-2014. *Annals of Glaciology* 58(75pt1):21-35.

Alley, W. M., T. E. Reilly, and O. L. Franke. 1999. *Sustainability of groundwater resources*. U.S. Geological Survey Circular 1186.

Arnaud, C. H. 2018. Shrinking mass specs. *Chemical and Engineering News* 96(22). Available at: https://cen.acs.org/analytical-chemistry/mass-spectrometry/Shrinking-mass-specs/96/i22 [Accessed June 11, 2018].

Banna, M. H., S. Imran, A. Francisque, H. Najjaran, R. Sadiq, M. Rodriguez, and M. Hoorfar. 2014. Online drinking water quality monitoring: Review on available and emerging technologies. *Critical Reviews in Environmental Science and Technology* 44(12):1370-1421.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438(17):303-309.

Barthel, R., and S. Banzhaf. 2015. Groundwater and surface water interaction at the regional scale: A review with focus on regional integrated models. *Water Resources Management* 30(1):1-32.

Barton, J., M. B. G. García, D. H. Santos, P. Fanjul-Bolado, A. Ribotti, M. McCaul, D. Diamond, and P. Magni. 2016. Screen-printed electrodes for environmental monitoring of heavy metal ions: A review. *Microchimica Acta* 183(2):503-517.

Bates, B., Z. W. Kundzewicz, S. Wu, and J. Palutikof. 2008. *Climate change and w*ater. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC) Secretariat.

Beddington, J. 2009. “Food, energy, water and the climate: A perfect storm of global events?” Lecture to Sustainable Development UK 09 Conference, Vol. 19. Government Office for Science, London.

Berner, R. A. 2003. The long-term carbon cycle, fossil fuels, and atmospheric composition. *Nature* 426(6964):322-326.

Blackhurst, B. M., C. Hendrickson, and J. S. I. Vidal. 2010. Direct and indirect water withdrawals for U.S. industrial sectors. *Environmental Science & Technology* 44(6):2126-2130.

Blanchard, S. F. 1999. *External task force review of the United States Geological Survey federal-state cooperative water program*. Reston, VA: U.S. Geological Survey Circular 1192.

Blazer, V. S., L. R. Iwanowicz, D. D. Iwanowicz, D. R. Smith, J. A. Young, J. D. Hendrick, S. W. Foster, and S. J. Reeser. 2007. Intersex (testicular oocytes) in smallmouth bass from the Potomac River and selected nearby drainages. *Journal of Aquatic Animal Health* 19(4):242-253.

Boehlert, B., K. M. Strzepek, S. C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J. E. Neumann, and J. Martinich. 2015. Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *Journal of Advances in Modeling Earth Systems* 7(3):1326-1338.

Bonan, G. B., and S. C. Doney. 2018. Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. *Science* 359(6375):eaam8328.

Boutt, D. F., D. W. Hyndman, B. C. Pijanowski, and D. T. Long. 2001. Identifying potential land use-derived solute sources to stream baseflow using groundwater models and GIS. *Groundwater* 39(1):24-34.

Boxall, A. B. A., M. A. Rudd, B. W. Brooks, D. J. Caldwell, K. Choi, S. Hickmann, E. Innes, K. Ostapyk, J. P. Staveley, T. Verslycke, G. T. Ankley, K. F. Beazley, S. E. Belanger, J. P. Berninger, P. Carriquiriborde, A. Coors, P. C. DeLeo, S. D. Dyer, J. F. Ericson, F. Gagné, J. P. Giesy, T. Gouin, L. Hallstrom, M. V. Karlsson, D. G. Joakim, Larsson, J. M. Lazorchak, F. Mastrocco, A. McLaughlin, M. E. McMaster, R. D. Meyerhoff, R. Moore, J. L. Parrott, J. R. Snape, R. Murray-Smith, M. R. Servos, P. K. Sibley, J. O. Straub, N. D. Szabo, E. Topp, G. R. Tetreault, V. L. Trudeau, and G. Van Der Kraak. 2012. Pharmaceuticals and personal care products in the environment: What are the big questions? *Environmental Health Perspectives* 120(9):1221-1229.

Boyce, C. K., and J. E. Lee. 2017. Plant evolution and climate over geological timescales. *Annual Review of Earth and Planetary Sciences* 45:61-87.

Brooks, M. H. 2001. *Cooperative water program - A partnership in the nation’s water-resources program*. Reston, VA: U.S. Geological Survey Fact Sheet 128-01.

Brown, C., and U. Lall. 2006. Water and economic development: The role of variability and a framework for resilience. *Natural Resources Forum* 30(4):306-317.

Buffle, J., and M. L. Tercier-Waeber. 2005. Voltammetric environmental trace-metal analysis and speciation: From laboratory to in situ measurements. *TrAC Trends in Analytical Chemistry* 24(3):172-191.

Campbell, C., R. Greenberg, D. Mankikar, and R. D. Ross. 2016. A case study of environmental injustice: The failure in Flint. *International Journal of Environmental Research and Public Health* 13(10):951.

Campos, C. J., J. Avant, N. Gustar, J. Lowther, A. Powell, L. Stockley, and D. N. Lees. 2015. Fate of human noroviruses in shellfish and water impacted by frequent sewage pollution events. *Environmental Science & Technology* 49(14):8377-8385.

Cantwell, M. G., M. M. Perron, J. C. Sullivan, D. R. Katz, R. M. Burgess, and J. King. 2014. *Environmental Monitoring and Assessment* 186(8):4841-4855.

Chaffin, J. D., D. D. Kane, K. Stanislawczyk, and E. M. Parker. 2018. Accuracy of data buoys for measurement of cyanobacteria, chlorophyll, and turbidity in a large lake (Lake Erie, North America): Implications for estimation of cyanobacterial bloom parameters from water quality sonde measurements. *Environmental Science and Pollution Research* 1-15.

Chao, B. F., Y. H. Wu, and Y. S. Li. 2008. Impact of artificial reservoir water impoundment on global sea level. *Science* 320(5873):212-214.

Chapra, S. C., B. Boehlert, C. Fant, V. J. Bierman, Jr., J. Henderson, D. Mills, D. M. L. Mas, L. Rennels, L. Jantarasami, J. Martinich, K. M. Strzepek, and H. W. Paerl. 2017. Climate change impacts on harmful algal blooms in U.S. freshwaters: A screening-level assessment. *Environmental Science & Technology* 51(16):8933-8943.

Chavez, M., M. Perez, C. Tunney, and S. Núñez. 2017. Accountability and transparency diluted in the Flint water crisis: A case of institutional implosion. *Norteamérica* 12(1):11-52.

Clark, M. P., Y. Fan, D. M. Lawrence, J. C. Adam, D. Bolster, D. J. Gochis, R. P. Hooper, M. Kumar, L. R. Leung, D. S. Mackay, R. M. Maxwell, C. Shen, S. C. Swenson, and X. Zeng. 2015. Improving the representation of hydrologic processes in Earth system models. *Water Resources Research* 51(8):5929-5956.

Cloke, H. L., and F. Papenberger. 2009. Ensemble flood forecasting: A review. *Journal of Hydrology* 375(3-4):613-626.

Cogan, D., C. Fay, D. Boyle, C. Osborne, N. Kent, J. Cleary, and D. Diamond. 2015. Development of a low-cost microfluidic sensor for the direct determination of nitrate using chromotropic acid in natural waters. *Analytical Methods* 7(13):5396-5405.

Cooley, H., N. Ajami, M. Ha, V. Srinivasan, J. Morrison, K. Donnelly, and J. Christian-Smith. 2013. *Global water governance in the 21st century*. Oakland, CA: Pacific Institute. Available at: http://pacinst.org/publication/global-water-governance-in-the-21st-century-2 [Accessed July 25, 2018].

Compton, J. E., D. J. Sobota, J. Lin, and M. Sengco. 2016. Ecosystem services impacts associated with environmental reactive nitrogen release in the United States. Proceedings of the 2016 International Nitrogen Initiative Conference. Melbourne, Australia, December 4-10, 2016.

Cook, B. I., T. R. Ault, and J. E. Smerdon. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sciences Advances* 1(1):e1400082. Available at: http://advances.sciencemag.org/content/1/1/e1400082 [Accessed September 4, 2018].

Cook, B. I., J. S. Mankin, and K. J. Anchukaitis. 2018. Climate Change and Drought: From Past to Future. *Current Climate Change Report* 4(2):164-179.

Davies, E. G. R., and S. P. Simonovic. 2011. Global water resources modeling with an integrated model of the social-economic-environmental system. *Advances in Water Resources* 34(6):684-700.

DeBeer, C. M., H. S. Wheater, S. K. Carey, and K. P. Chun. 2016. Recent climatic, cryospheric, and hydrological changes over the interior of Western Canada: A review and synthesis. *Hydrology and Earth System Sciences* 20(4):1573-1598.

Diaz, R. J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321(5891):926-929.

Dieter, C. A., M. A. Maupin, R. R. Caldwell, M. A. Harris, T. I. Ivahnenko, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2018. *Estimated use of water in the United States in 2015*. Reston, VA: U.S. Geological Survey Circular 1441.

Diffenbaugh, N. S., D. L. Swain, and D. Touma. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America* 112(13):3931-3936.

DOI (U.S. Department of the Interior). 2018. *Budget Justifications and Performance Information Fiscal Year 2019 U.S. Geological Survey*. The Department of the Interior. Available at: https://www.doi.gov/sites/doi.gov/files/uploads/fy2019_usgs_budget_justifica-tion.pdf [Accessed August 21, 2018].

Dunning, C. P., D. T. Feinstein, C. A. Buchwald, R. J. Hunt, and M. J. Haserodt. 2017. *Estimation of the groundwater resources of the bedrock aquifers at the Kettle Moraine Springs State Fish Hatchery, Sheboygan County, Wisconsin*. U.S. Geological Survey Scientific Investigations Report 2017–5074. Available at: https://doi.org/10.3133/sir20175074 [Accessed July 25, 2018].

Durack, P. J., S. E. Wijffels, and R. J. Matear. 2012. Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* 336(6080):455-458.

Eagleson, P. S. 1986. The emergence of global-scale hydrology. *Water Resources Research* 22(9S):6S-14S.

EPA (U.S. Environmental Protection Agency). 2016. *Climate change indicators in the United States. Fourth Edition*. EPA 430-R-16-004. Available at: https://www.epa.gov/climate-indicators [Accessed June 21, 2018].

EPA. 2017. *Emergency response and management report, fall 2017*. Available at: https://www.epa.gov/emergency-response/emergency-response-and-management-activities#fall2017 [Accessed June 21, 2018].

Epstein, P. R. 2005. Climate change and human health. *New England Journal of Medicine* 353(14):1433-1436.

Evans, R. G., and E. J. Sadler. 2008. Methods and technologies to improve efficiency of water use. *Water Resources Research* 44(7):WW00E04.

Evenson, E. J., R. C. Orndorff, C. D. Blome, J. K. Böhlke, P. K. Hershberger, V. E. Langenheim, G. J. McCabe, S. E. Morlock, H. W. Reeves, J. P. Verdin, H. S. Weyers, and T. M. Wood. 2013. *U.S. Geological Survey water science strategy: Observing, understanding, predicting, and delivering water science to the nation*. Reston, VA: U.S. Geological Survey Circular 1383-G.

Field, J. A., C. A. Johnson, and J. B. Rose. 2006. What is “emerging”? *Environmental Science & Technology* 40(23):7105.

Focazio, M. J., D. W. Kolpin, K. K. Barnes, E. T. Furlong, M. T. Meyer, S. D. Zaugg, L. B. Barber, and M. E. Thurman. 2008. A national reconnaissance for pharmaceuticals and other organic wastewater contaminants in the United States–II. Untreated drinking water sources. *Science of the Total Environment* 402(2-3):201-216.

Galloway, G. E. 2011. If stationarity is dead, what do we do now? *Journal of the American Water Resources Association* 47(3):563-570.

Garcia, M., K. Portney, and S. Islam. 2016. A question driven socio-hydrological modeling process. *Hydrology and Earth System Sciences* 20(1):73-92.

Georgakakos, A., P. Fleming, M. Dettinger, and C. Peters-Lidard. 2014. *Water resources*. Pp. 69-112 in *Climate change impacts in the United States: The third National Climate Assessment*. Washington, DC: U.S. Global Change Research Program.

Gilliom, R. J. 2007. Pesticides in U.S. streams and groundwater. *Environmental Science & Technology* 41(10):3408-3414.

Giorgi, F., E. S. Im, and E. Coppola. 2011. Higher hydroclimatic intensity with global warming. *Journal of Climate* 24:5309-5324.

Gleeson, T., K. M. Befus, S. Jasechko, E. Luijendijk, and M. B. Cardenas. 2016. The global volume and distribution of modern groundwater. *Nature Geoscience* 9(2):161-167.

Gleick, P. H. 2003a. Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302(5650):1524-1528.

Gleick, P. H. 2003b. Water use. *Annual Review of Environment and Resources* 28(1):275-314.

Gleick, P. H. 2017. *Impacts of California's five-year (2012–2016) drought on hydroelectricity generation*. Oakland, CA: Pacific Institute. Available at: http://pacinst.org/publication/impacts-californias-five-year-2012-2016-drought-hydroelectricity-generation [Accessed July 25, 2018].

Gleick, P. H., H. Cooley, J. S. Famiglietti, D. P. Lettenmaier, T. Oki, C. J. Vörösmarty, and E. F. Wood. 2013. *Improving understanding of the global hydrologic cycle: Observation and analysis of the climate system: The global water cycle*. In *Climate science for serving society: Research, modeling, and prediction priorities,* G. R. Asrar and J. W. Hurrell, eds. Dordrecht, Netherlands: Springer.

Gober, P. 2018. *Building resilience for uncertain water futures*. Cham, Switzerland: Palgrave Macmillan.

Gober, P., and H. S. Wheater. 2015. Debates—Perspectives on sociohydrology: Modeling flood risk as a public policy problem. *Water Resources Research* 51(6):4782-4788.

Good, S. P., D. Noone, and G. Bowen. 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science* 349(6244):175-177.

Granell, C., D. Havlik, S. Schade, Z. Sabeur, C. Delaney, J. Pielorz, T. Usländer, P. Mazzetti, K. Schleidt, M. Kobernus, F. Havlik, N. R. Bodsberg, A. Berre, and J. L. Mon. 2016. Future Internet technologies for environmental applications. *Environmental Modelling and Software* 78:1-15.

Grant, E. G., C. L. Tague, and C. D. Allen. 2013. Watering the forest for the trees: An emerging priority for managing water in forest landscape. *Frontiers in Ecology and the Environment* 11(6):314-321.

Green, T. R., M. Taniguchi, H. Kooi, J. J. Gurdak, D. M. Allen, K. M. Hiscock, H. Treidel, A. Aureli. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology* 405(3-4):532-560.

Griffin, D., and J. K. Anchukaitis. 2014. How unusual is the 2012–2014 California drought? *Geophysical Research Letters* 41(24):9017-9023.

GW Milken Institute SPH (Milken Institute School of Public Health). 2018. *Ascertainment of the estimated excess mortality from Hurricane Maria in Puerto Rico in collaboration with the University of Puerto Rico Graduate School of Public Health*. The George Washington University. Available at: https://publichealth.gwu.edu/content/gw-report-delivers-recommendations-aimed-preparing-puerto-rico-hurricane-season [Accessed September 4, 2018].

Haddeland, I., J. Heinke, H. Biemans, S. Eisner, M. Flörke, N. Hanasaki, M. Konzmann, F. Ludwig, Y. Masaki, J. Schewe, and T. Stacke. 2014. Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences of the United States of America* 111(9):3251-3256.

Hansen, A. T., C. L. Dolph, E. Foufoula-Georgiou, and J. C. Finlay. 2018. Contribution of wetlands to nitrate removal at the watershed scale. *Nature Geoscience* 11:127-132.

Hutson, S. S., N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia, and M. A. Maupin. 2004. *Estimated use of water in the United States in 2000*. Reston, VA: U.S. Geological Survey, U.S. Government Printing Office.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate change 2013: The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, eds. Cambridge, UK: Cambridge University Press.

Jaeger, W. K. 2015. *Institutions and water*. Pp. 13-31 in *Handbook of water economics*, A. Dinar, and K. Schwabe, eds. Northampton, MA: Edward Elgar Publishing.

Jaeger, W. K., A. Amos, D. P. Bigelow, H. Chang, D. R. Conklin, R. Haggerty, C. Langpap, K. Moore, P. W. Mote, A. W. Nolin, A. J. Plantinga, C. L. Schwartz, D. Tullos, and D. P. Turner. 2017. Finding water scarcity amid abundance using human–natural system models. *Proceedings of the National Academy of Sciences of the United States of America* 114(45):11884-11889.

Jetoo, S., V. I. Grover, and G. Krantzberg. 2015. The Toledo drinking water advisory: Suggested application of the water safety planning approach. *Sustainability* 7(8):9787-9808.

Jiménez Cisneros, B. E., T. Oki, N. W. Arnell, G. Benito, J. G. Cogley, P. Doll, T. Jiang, and S. S. Mwakalila. 2014. *Freshwater resources*. Pp. 229-269 in *Climate change 2014: Impacts, adaptation, and vulnerability: Part A: Global and sectoral aspects*, C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Gimma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, eds. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Kaushal, S. S., P. M. Groffman, G. E. Likens, K. T. Belt, W. P. Stack, V. R. Kelly, L. E. Band, and G. T. Fisher. 2005. Increased salinization of freshwater in the northeastern United States. *Proceedings of the National Academy of Sciences of the United States of America* 102(38):13517-13520.

Kaushal, S. S., W. H. McDowell, and W. M. Wollheim. 2014. Tracking evolution of urban biogeochemical cycles: Past, present, and future. *Biogeochemistry* 121(1):1-21.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin. 2009. *Estimated use of water in the United States in 2005*. Reston, VA: U.S. Geological Survey Circular 1344.

Khatri, N., and S. Tyagi. 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science* 8(1):23-39.

Khedun, C. P., and V. P. Singh. 2013. Climate change, water, and health: A review of regional challenges. *Water Quality, Exposure, and Health* 6(1-2):7-17.

Kingdon, A., J. R. A. Giles, and J. P. Lowndes. 2014. Future of technology in NERC data models and informatics: Outputs from InformaTEC. *Geological Society, London, Special Publications* 408:245-253.

Kishore, N., D. Marqués, A. Mahmud, M. V. Kiang, I. Rodriguez, A. Fuller, P. Ebner, C. Sorensen, F. Racy, J. Lemery, L. Maas, J. Leaning, R. A. Irizarry, S. Balsari, and C. O. Buckee. 2018. Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine* 379:162-170.

Kling, H. J., S. B. Watson, G. K. McCullough, and M. P. Stainton. 2011. Bloom development and phytoplankton succession in Lake Winnipeg: A comparison of historical records with recent data. *Aquatic Ecosystem Health & Management* 14(2):219-224.

Kolpin, D. W., E. T. Furlong, M. T. Meyer, E. M. Thurman, S. D. Zaugg, L. B. Barber, and H. T. Buxton. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999-2000: A national reconnaissance. *Environmental Science & Technology* 36(6):1202-1211.

Korenaga, J., N. J. Planavsky, and D. A. Evans. 2017. Global water cycle and the coevolution of the Earth's interior and surface environment. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 375(2094):20150393.

Kovacic, D., R. M. Twait, M. P. Wallace, and J. M. Bowling. 2006. Use of created wetlands to improve water quality in the Midwest – Lake Bloomington case study. *Ecological Engineering* 28(3):258-270.

Lauffenburger, Z. H., J. J. Gurdak, C. Hobza, D. Woodward, and C. Wolf. 2018. Irrigated agriculture and future climate change effects on groundwater recharge, northern High Plains aquifer, USA. *Agricultural Water Management* 204:69-80.

Lei, M., L. Zhang, J. Lei, L. Zong, J. Li, Z. Wu, and Z. Wang. 2015. Overview of emerging contaminants and associated human health effects. *BioMed Research International* 2015:404796.

Lempert, R. J., and M. E. Schlesiger. 2000. Robust strategies for abating climate change. *Climatic Change* 45(3-4):387-401.

Lempert, R. J., S. W. Poper, and S. C. Bankes. 2003. *Shaping the next 100 years: New methods of long-term policy analysis*. Santa Monica, CA: RAND.

Lettenmaier, D. P., D. Alsdorf, J. Dozier, G. J. Huffman, M. Pan, and E. F. Wood. Inroads of remote sensing into hydrologic science during the WRR era. *Water Resources Research* 51(9):7309-7342.

Levy, Z. F., D. O. Rosenberry, R. Moucha, D. M. Mushet, M. B. Goldhaber, J. W. LaBaugh, A. J. Fiorentino, and D. I. Siegel. 2018. Drought-induced recharge promotes long-term storage of porewater salinity beneath a prairie wetland. *Journal of Hydrology* 557:391-406.

Lukacs, H. A., N. Sawe, and N. Ulibarri. 2017. Risk, uncertainty, and institutional failure in the 2014 West Virginia chemical spill. *Case Studies in the Environment*, September 2017. University of California Press.

MacDonald, G. M. 2010. Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences of the United States of America* 107(50):21256-21262.

Maher, K., and C. P. Chamberlain. 2014. Hydrologic regulation of chemical weathering and the geologic carbon cycle. *Science* 343(6178):1502-1504.

Maier, H. R., J. H. A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and J. H. Kwakkel. 2016. An uncertain future, deep uncertainty, scenarios, robustness, and adaptation: How do they fit together? *Environmental Modelling & Software* 81:154-164.

Malham, S. K., P. Rajko-Nenow, E. Howlett, K. E. Tuson, T. L. Perkins, D. W. Pallett, H. Wang, C. F. Jago, D. L. Jones, and J. E. McDonald. 2014. The interaction of human microbial pathogens, particulate material, and nutrients in estuarine environments and their impacts on recreational and shellfish waters. *Environmental Science: Processes & Impacts* 16(9):2145-2155.

Mankin, J. S., D. Viviroli, D. Singh, A. Y. Hoekstra, and N. S. Diffengaugh. 2015. The potential for snow to supply human water demand in the present and future. *Environmental Research Letters* 10(11):114016.

Mann, M. E., and P. H. Gleick. 2015. Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America* 112(13):3858-3859.

Maupin, M. A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2014. *Estimated use of water in the United States in 2010.* Reston, VA: U.S. Geological Survey Circular 1405.

Mbaka, J. G., and M. W. Mwaniki. 2017. A critical review of the effect of water storage reservoirs on organic matter decomposition in rivers. *Environmental Reviews* 25(2):193-198.

McGuire, V. L. 2017. *Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2015 and 2013-15*. U.S. Geological Survey Scientific Investigations Report 2017-5040. Available at: https://doi.org/10.3133/sir20175040 [Accessed July 25, 2018].

McKenna, O. P., D. M. Mushet, D. O. Rosenberry, and J. W. LaBaugh. 2017. Evidence for a climate-induced ecohydrological state shift in wetland ecosystems of the southern prairie pothole region. *Climatic Change* 145(3-4):273-287.

McMichael, A. J., R. E. Woodruff, and S. Hales. Climate change and human health: Present and future risks. *The Lancet* 367(9513):859-869.

McNabb, D. E. (2017). *Managing water conflicts*. Pp. 187-213 in *Water resource management*. Cham, Switzerland: Palgrave Macmillan.

Michalak, A. M. 2016. Study role of climate change in extreme threats to water quality. *Nature* 535(7612):349-352.

Michalak, A. M., E. J. Anderson, D. Beletsky, S. Boland, N. S. Bosch, T. B. Bridgeman, J. D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J. V. DePinto, M. A. Evans, G. L. Fahnenstiel, L. He, J. C. Ho, L. Jenkins, T. H. Johengen, K. C. Kuo, E. LaPorte, X. Liu, M. R. McWilliams, M. R. Moore, D. J. Posselt, R. P. Richards, D. Scavia, A. L. Steiner, E. Verhamme, D. M. Wright, and M. A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences of the United States of America* 110(16):6448-6452.

Milly, P. C. D., J. J. Betancourt, M. Falkenmark, R. M. Hirsh, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319(5863):573-574.

Moody, D. W. 1990. Groundwater contamination in the United States. *Journal of Soil and Water Conservation* 45(2):170-179.

Moran, M. J., J. S. Zogorski, and P. J. Squillace. 2007. Chlorinated solvents in groundwater of the United States. *Environmental Science & Technology* 41(1):74-81.

Moschet, C., I. Wittmer, J. Simovic, M. Junghans, A. Piazzoli, H. Singer, C. Stamm, C. Leu, and J. Hollender. 2014. How a complete pesticide screening changes the assessment of surface water quality. *Environmental Science & Technology* 48(10):5423-5432.

Mote, P. W., S. Li, D. P. Lettenmaier, M. Xiao, and R. Engel. 2018. Dramatic declines in snowpack in the western U.S. *Climate and Atmospheric Science* 1(2).

Mushet, D. M., O. P. McKenna, J. W. LaBaugh, N. H. Euliss, and D. O. Rosenberry. 2018. Accommodating state shifts within the conceptual framework of the wetland continuum. *Wetlands* 38(141):1-5.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. *Flowback and produced waters: Opportunities and challenges for innovation: Proceedings of a workshop*. Washington, DC: The National Academies Press.

NASEM. 2018a. *Thriving on our changing planet: A decadal strategy for Earth observation from space.* Washington, DC: The National Academies Press.

NASEM. 2018b. *Review of the New York City Department of Environmental Protection Operations Support Tool for Water Supply*. Washington, DC: The National Academies Press.

Nielsen-Gammon, J. W. 2012. The 2011 Texas drought. *Texas Water Journal* 3(1):59-95.

Nilsson, C., C. A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308(5720):405-408.

Nordstrom, D. K. 2002. Worldwide occurrences of arsenic in groundwater. *Science* 296:2143-2145.

Novak, R., J. G. Kennen, R. W. Abele, C. F. Baschon, D. M. Carlisle, L. Dlugolecki, D. M. Eignor, J. E. Flotemersch, P. Ford, J. Fowler, R. Galer, L. Perras Gordon, S. E. Hansen, B. Herbold, T. E. Johnson, J. M. Johnston, C. P. Konrad, B. Leamond, and P. W. Seelbach. 2016. *Final EPA-USGS technical report: Protecting aquatic life from effects of hydrologic alteration. EPA Report 822-R-16-007*, U.S. Geological Survey Scientific Investigations Report 5164. Available at: http://pubs.usgs.gov/sir/2015/5160/ and http://www2.epa.gov/wqc/aquatic life-ambient-water quality-criteria [Accessed July 25, 2018].

NRC (National Research Council). 1991. *Opportunities in the hydrologic sciences*. Washington, DC: National Academy Press.

NRC. 2001. *Grand challenges in environmental sciences*. Washington, DC: National Academy Press.

NRC. 2007. *Surface temperature reconstructions for the last 2,000 years*. Washington, DC: The National Academies Press.

NRC. 2008. *Integrating multiscale observations of U.S. waters*. Washington, DC: The National Academies Press.

NRC. 2009. *Toward a sustainable and secure water future: A leadership role for the U.S. Geological Survey*. Washington, DC: The National Academies Press.

NRC. 2011. *Global change and extreme hydrology*. Washington, DC: The National Academies Press.

NRC. 2012a. *Challenges and opportunities in the hydrologic sciences*. Washington, DC: The National Academies Press.

NRC. 2012b. *Climate change: Evidence, impacts, and choices*. Set of two booklets, with DVD. Washington, DC: The National Academies Press.

NRC. 2012c. *Himalayan glaciers: Climate change, water resources, and water security*. Washington, DC: The National Academies Press.

NRC. 2012d. *Preparing for the third decade of the National Water-Quality Assessment Program*. Washington, DC: The National Academies Press.

NRC. 2013. *Alternatives for managing the nation's complex contaminated groundwater sites*. Washington, DC: The National Academies Press.

NSTC (National Science and Technology Council) Subcommittee on Ocean Science and Technology. 2016. *Harmful algal blooms and hypoxia comprehensive research plan and action strategy: An interagency report*. Interagency Working Group on the Harmful Algal Bloom and Hypoxia Research and Control Act. February 11, 2016.

Orloff, K. G., K. Mistry, P. Charp, S. Metcalf, R. Marino, T. Shelly, E. Melaro, A. M. Donohoe, and R. L. Jones. 2004. Human exposure to uranium in groundwater. *Environmental Research* 94(3):319-326.

Paerl, H. W., and T. G. Otten. 2013. Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology* 65(4):995-1010.

Pandve, H. T. 2010. Climate change and health: Research challenges for health in the developing countries. *Indian Journal of Occupational and Environmental Medicine* 14(2):42-44.

Patel, A. I., and L. A. Schmidt. 2017. Water access in the United States: Health disparities abound and solutions are urgently needed. *American Journal of Public Health* 107(9):1354-1356.

Patterson, L., M. Doyle, K. King, and D. Monsma. 2017. *Internet of water: Sharing and integrating water data for sustainability*. A report from the Aspen Institute Dialogue Series on Water Data. Washington, DC: The Aspen Institute.

Pavelsky, T. M., M. T. Durand, K. M. Andreadis, R. E. Beighley, R. C. Paiva, G. H. Allen, and Z. F. Miller. 2014. Assessing the potential global extent of SWOT river discharge observations. *Journal of Hydrology* 519(Part B):1516-1525.

Pepin, N., R. S. Bradley, H. F. Diaz, M. Baraer, E. B. Caceres, N. Forsythe, H. Fowler, G. Greenwood, M. Z. Hashmi, X. D. Liu, J. R. Miller, L. Ning, A. Ohmura, E. Palazzi, I. Rangwala, W. Schoner, I. Severskiy, M. Shahgedanova, M. B. Wang, S. N. Williamson, D. Q. Yang, and Mt Res Initiative EDW Working Group. 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change* 5(5):424-430.

Perrone, D., and G. M. Hornberger. 2013. Water, food, and energy security: Scrambling for resources or solutions? *Wiley Interdisciplinary Reviews: Water* 1(1):49-68.

Peters, N. E, and M. Meybeck. 2000. Water quality degradation effects on freshwater availability: Impacts of human activities. *Water International* 25(2):185-193.

Pressman, J. G., S. D. Richardson, T. F. Speth, R. J. Miltner, M. G. Narotsky, E. S. Hunter, III, G. E. Rice, L. K. Teuschler, A. McDonald, S. Parvez, S. W. Krasner, H. S. Weinberg, A. B. McKague, C. J. Parrett, N. Bodin, R. Chinn, C.-F. T. Lee, and J. E. Simmons. 2010. Concentration, chlorination, and chemical analysis of drinking water for disinfection byproduct mixtures health effects research: U.S. EPA's four lab study. *Environmental Science & Technology* 44(19):7184-7192.

Poff, L., and J. H. K. Zimmerman. 2009. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology* 55(1):194-205.

Polade, S. D., A. Gershunov, D. R. Cayan, M. D. Dettinger, and D. W. Pierce. 2017. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports* 7(10783):1-10.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman, Jr. 2002. Gulf of Mexico hypoxia, a.k.a. “the dead zone.” *Annual Review of Ecology and Systematics* 33:235-263.

Rasmussen, R., C. Liu, K. Ikeda, D. Gochis, D. Yates, F. Chen, M. Tewari, M. Barlage, J. Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, and E. Gutmann. 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *Journal of Climate* 24(12):3015-3048.

Refsgaard, J. C., A. L. Hojberg, I. Moller, M. Hansen, and V. Sondergaard. 2010. Groundwater modeling in integrated water resources management—Visions for 2020. *Groundwater* 48(5):633-648.

Regan, R. S., S. L. Markstrom, L. E. Hay, R. J. Viger, P. A. Norton, J. M. Driscoll, and J. H. LaFontaine. 2018. *Description of the national hydrologic model for use with the Precipitation-Runoff Modeling System (PRMS).* U.S. Geological Survey Techniques and Methods 6-B9.

Renner, R. 2004. Plumbing the depths of D.C.’s drinking water crisis. *Environmental Science & Technology* 38(12):224A-227A.

Repetto, R. 2012. *Economic and environmental impacts of climate change in Arizona*. New York NY: Demos.

Richardson, D. M., P. M. Holmes, K. J. Esler, S. M. Galatowitsch, J. C. Stromberg, S. P. Kirkman, P. Pyšek, and R. J. Hobbs. 2007. Riparian vegetation: Degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions* 13(1):126-139.

Richardson, S. D., and T. A. Ternes. 2009. Water analysis: Emerging contaminants and current issues. *Analytical Chemistry* 81(12):4645-4677.

Rivett, M. O., S. R. Buss, P. Morgan, J. W. Smith, and C. D. Bemment. 2008. Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. *Water Research* 42(16):4215-4232.

Roberston, D. M., G. E. Schwarz, D. A. Saad, and R. B. Alexander. 2009. Incorporating uncertainty into the ranking of SPARROW Model nutrient yields form Mississippi/Atchafalaya River Basin Watersheds. *Journal of the American Water Resources Association* 45(2):534-549.

Rosenzweig, C., and W. Solecki. 2014. Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change* 28:395-408.

Rosi-Marshall, E. J., D. W. Kincaid, H. A. Bechtold, T. V. Royer, M. Rojas, and J. J. Kelly. 2013. Pharmaceuticals suppress algal growth and microbial respiration and alter bacterial communities in stream biofilms. *Ecological Applications* 23(3):583-593.

Rosi-Marshall, E. J., D. Snow, S. L. Bartelt-Hunt, A. Paspalof, and J. L. Tank. 2014. A review of ecological effects and environmental fate of illicit drugs in aquatic ecosystems. *Journal of Hazardous Materials* 282:18-25.

Sanders, K. T., and S. F. Masri. 2016. The energy-water agriculture nexus: The past, present, and future of holistic resource management via remote sensing technologies. *Journal of Cleaner Production* 117:73-88.

Scanlon, B. R., B. L. Ruddell, P. M. Reed, R. I. Hook, C. Zheng, V. C. Tidwell, and S. Siebert. 2017. The food-energy-water nexus: Transforming science for society. *Water Resources Research* 53(5):3550-3556.

Schlesinger, W. H., and E. S. Bernhardt. 2013. *Wetland ecosystems*. Pp. 233-274 in *Biogeochemistry: An analysis of global change, third edition*. New York NY: Elsevier/Academic Press.

Schultz, M. M., E. T. Furlong, D. W. Kolpin, S. L. Werner, H. L. Schoenfuss, L. B. Barber, and A. M. Vajda. 2010. Antidepressant pharmaceuticals in two U.S. effluent-impacted streams: Occurrence and fate in water and sediment, and selective uptake in fish neural tissue. *Environmental Science & Technology* 44(6):1918-1925.

Sheffield, J., E. F. Wood, N. Chaney, K. Guan, S. Sadri, and X. Yuan. 2014. A drought monitoring and forecasting system for sub-Sahara African water resources and food security. *Bulletin of the American Meteorological Society* 95(6):861-882.

Shevliakova, E., R. J. Stouffer, S. Malyshev, J. P. Krasting, G. C. Hurtt, and S. W. Pacala. 2013. Historical warming reduced due to enhanced land carbon uptake. *Proceedings of National Academy of Sciences of the United States of America* 110(42):16730-16735.

Shoda, M. E., T. R. Lathrop, and M. R. Risch. 2015. *Real-time, continuous water quality monitoring in Indiana and Kentucky*. U.S. Geological Survey Fact Sheet 2015-3041. Available at: https://dx.doi.org/10.3133/fs20153041 [Accessed September 4, 2018].

Siegrist, R. L., 2017. *Contemporary water use and wastewater generation*. Pp. 81-140 in *Decentralized water reclamation engineering*. Cham, Switzerland: Springer.

Snyder, D. T., C. J. Pulliam, Z. Ouyang, and R. G. Cooks. 2015. Miniature and fieldable mass spectrometers: Recent advances. *Analytical Chemistry* 88(1):2-29.

Solander, K. C., J. T. Reager, and J. S. Famiglietti. 2016. How well will the Surface Water and Ocean Topography (SWOT) mission observe global reservoirs? *Water Resources Research* 52(3):2123-2140.

Solander, K. C., J. T. Reager, Y. Wada, J. S. Famiglietti, and R. S. Middleton. 2017. GRACE satellite observations reveal the severity of recent water over-consumption in the United States. *Scientific Reports* 7(1):8723.

Soller, J. A., M. E. Schoen, T. Bartrand, J. E. Ravenscroft, and N. J. Ashbolt. 2010. Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water Research* 44(16):4674-4691.

Stebbins, G. L. 1952. Aridity as a stimulus to plant evolution. *The American Naturalist* 86(826): 33-44.

Steffen, M. M., T. W. Davis, R. M. L. McKay, G. S. Bullerjahn, L. E. Krausfeldt, J. M. A. Stough, M. L. Neitzey, N. E. Gilbert, G. L. Boyer, T. H. Johengen, D. C. Gossiaux, A. M. Burtner, D. Palladino, M. D. Rowe, G. J. Dick, K. A. Meyer, S. Levy, B. E. Boone, R. P. Stumpf, T. T. Wynne, P. V. Zimba, D. Gutierrez, and S. W. Wilhelm. 2017. Ecophysiological examination of the Lake Erie microcystis bloom in 2014: Linkages between biology and the water supply shutdown of Toledo, OH. *Environmental Science & Technology* 51(12):6745-6755.

Sterling, S. M., A. Ducharne, and J. Polcher. 2013. The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change* 3(4):385-390.

Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters* 5(4):044012.

Stuckey, A. October 25, 2017. Private water wells in Texas test positive for contamination after Harvey. *The Houston Chronicle*. Available at: https://www.chron.com/news/houston-texas/houston/article/Private-water-wells-in-Texas-test-positive-for-12306926.php [Accessed June 18, 2018].

Syed, T. H., J. S. Famiglietti, D. P. Chambers, J. K. Willis, and K. Hilburn. 2010. Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge. *Proceedings of the National Academy of Sciences of the United States of America* 107(42):17916-17921.

ter Schiphorst, J., J. Saez, D. Diamond, F. Benito-Lopez, and A. P. Schenning. 2018. Light-responsive polymers for microfluidic applications. *Lab on a Chip* 18(5):699-709.

Trenberth, K. E. 2010. More knowledge, less cert ainty. *Nature Reports Climate Change* 4(2):20-21.

Trenberth, K. E. 2011. Changes in precipitation with climate change. *Climate Research* 47(1-2):123-138.

USGCRP (U.S. Global Change Research Program). 2017. *Climate science special report: Fourth National Climate Assessment, Volume I*. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. U.S. Global Change Research Program, Washington, DC, USA. doi: 10.7930/J0J964J6.

USGS (U.S. Geological Survey). 2015. Bureau Workforce Plan: 2015-2020. U.S. Geological Survey.

Van Eekelen, M. W., W. G. M. Bastiaanssen, C. Jarmain, B. Jackson, F. Ferreira, P. van der Zaag, A. S. Okello, J. Bosch, P. Dye, E. Bastidas-Obando, R. J. J. Dost, and W. M. J. Luxemburg. 2015. A novel approach to estimate direct and indirect water withdrawals from satellite measurements: A case study from the Incomati basin. *Agriculture, Ecosystems & Environment* 200:126-142.

VanMetre, P. C., B. J. Mahler, D. Carlisle, and J. Coles. 2017. *Midwest stream quality assessment—Influences of human activities on streams*. USGS Numbered Series Fact Sheet 2017-3087.

Vaux, H. 2012. Water for agriculture and the environment: The ultimate trade-off. *The International Water Association* 14(S1):136-146.

Vidic, R. D., S. L. Brantley, J. M. Vandenbossche, D. Yoxtheimer, and J. D. Abad. 2013. Impact of shale gas development on regional water quality. *Science* 340(6134):1235009.

Vogel, R. M., U. Lall, X. Cai, B. Rajagopalan, P. K. Weiskel, R. P. Hooper, and N. C. Matalas. 2015. Hydrology: The interdisciplinary science of water. *Water Resources Research* 51(6):4409-4430.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289(5477):284-288.

Vörösmarty, C. J., D. Lettenmaier, C. Leveque, M. Meybeck, C. Pahl-Wostl, J. Alcamo, W. Cosgrove, H. Grassl, H. Hoff, P. Kabat, and F. Lansigan. 2004. Humans transforming the global water system. *Eos, Transactions American Geophysical Union* 85(48):509-514.

Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. Reidy Liermann, and P. M. Davies. 2010. Global threats to human water security and river biodiversity. *Nature* 467:555-561.

Wagner, R. J., R. W. Boulger, Jr., C. J. Oblinger, and B. A. Smith. 2006. *Guidelines and standard procedures for continuous water-quality monitors: Station operation, record computation, and data reporting*. U.S. Geological Survey Techniques and Methods 1-D3.

Wheater, H. S. 2006. Flood hazard and management: A U.K. perspective. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 364(1845):2135-2145.

Wheater, H. S., and P. Gober. 2015. Water security and the science agenda. *Water Resources Research* 51(7):5406-5424.

Whelton, A. J., L. McMillan, C. L.-R. Novy, K. D. White, and X. Huang. 2017. Case study: The crude MCHM chemical spill investigation and recovery in West Virginia USA. *Environmental Science: Water Research & Technology* 3(2):312-332.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. A. Alley. 1998. *Groundwater and surface water: A single resource.* U.S. Geological Survey Circular 1139.

World Bank. 2012. *Thai flood 2011: Rapid assessment for resilient recovery and reconstruction planning: Overview (English)*. Washington, DC: World Bank. Available at: http://documents.worldbank.org/curated/en/677841468335414861/Overview [Accessed July 25, 2018].

Wymore, A. S., J. Potter, B. Rodríguez-Cardona, and W. H. McDowell. 2018. Using in-situ optical sensors to understand the biogeochemistry of dissolved organic matter across a stream network. *Water Resources Research* 54(4):2949-2958.

Young, P.C. 2002. Advances in real-time flood forecasting. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 360(1796):1433-1450.

Yusa, A., P. Berry, J. J. Cheng, N. Ogden, B. Bonsal, R. Stewart, and R. Waldick. 2015. Climate change, drought, and human health in Canada. *International Journal of Environmental Research and Public Health* 12(7):8359-8412.

Zeng, T., Chin, Y. P., and W. A. Arnold. 2012. Potential for abiotic reduction of pesticides in prairie pothole porewaters. *Environmental Science & Technology* 46(6):3177-3187.

Zimmermann, E., L. Bracalenti, R. Piacentini, and L. Inostroza. 2016. Urban flood risk reduction by increasing green areas for adaptation to climate change. *Procedia Engineering* 161:2241-2246.

Zuniga, J.E. 2000. The Central Arizona Project. U.S. Bureau of Reclamation. Available at: http://www.riversimulator.org/Resources/States/CAPHistory.pdf [Accessed June 11, 2018].

A
The U.S. Geological Survey Water Mission Area

Since its inception after passage of the Organic Act (43 U.S.C. § 31) in 1879, the U.S. Geological Survey (USGS) has collected and stored scientific information that is compiled into long-term continuous datasets accessible by federal, state, and local agencies, the private sector, and the public. In general, USGS does not have regulatory authority[1] nor the authority to manage large tracts of public lands, construct infrastructure, or modify waterways or habitat.

The Water Mission Area (WMA) is one of seven interdisciplinary mission areas at USGS that emerged from a reorganization following the USGS 2007–2017 *Water Science Strategy* (Evenson et al., 2013). It covers scientific activities that involve collecting, assessing, and disseminating hydrological data and analyzing and researching hydrological systems. WMA is recognized for its high-quality, unbiased hydrologic data and scientific information. USGS is the world's largest outlet of water data, integrating nearly 350 million sample results from more than 400 organizations.[2] In addition to the millions of monthly users of online data, USGS delivers numerous scientific reports and journal articles annually.[3] These peer-reviewed publications are highly regarded for their scientific integrity and lack of bias.

As of 2018, WMA has a workforce of approximately 3,750 staff at state and regional Water Science Centers (WSCs) and headquarters.[4] More than 60 percent of WMA personnel are classified as hydrologists or hydrologic technicians (see Figure A.1), reflecting its current emphasis on collection and analysis of water resources data. Other important employment categories under the current organization include computer scientists, chemists, biologists, and ecologists, in addition to administrators. As the primary federal agency for water information, WMA monitors and assesses the quantity and characteristics of the nation's water resources, investigates the sources and behavior of natural solutes and contaminants in water (often with state cooperators and partners), and develops practical tools to improve understanding and management of this resource.

---

[1] Following a 1954 Supreme Court ruling, USGS serves as River Master on the Delaware River, coordinating the release of water (among Delaware, New Jersey, New York, New York City, and Pennsylvania) to ensure sufficient water quantity to meet downstream flow objectives (https://webapps.usgs.gov/odrm).

[2] Data provided to the committee by Drs. Nate Booth and Jordan Read, USGS WMA, at the committee's third meeting on February 8, 2018.

[3] Data provided to the committee by Drs. Nate Booth and Jordan Read, USGS WMA, at the committee's third meeting on February 8, 2018.

[4] Data provided to the committee by Dr. Don Cline, USGS associate director for water, at the committee's first meeting on September 18, 2017.

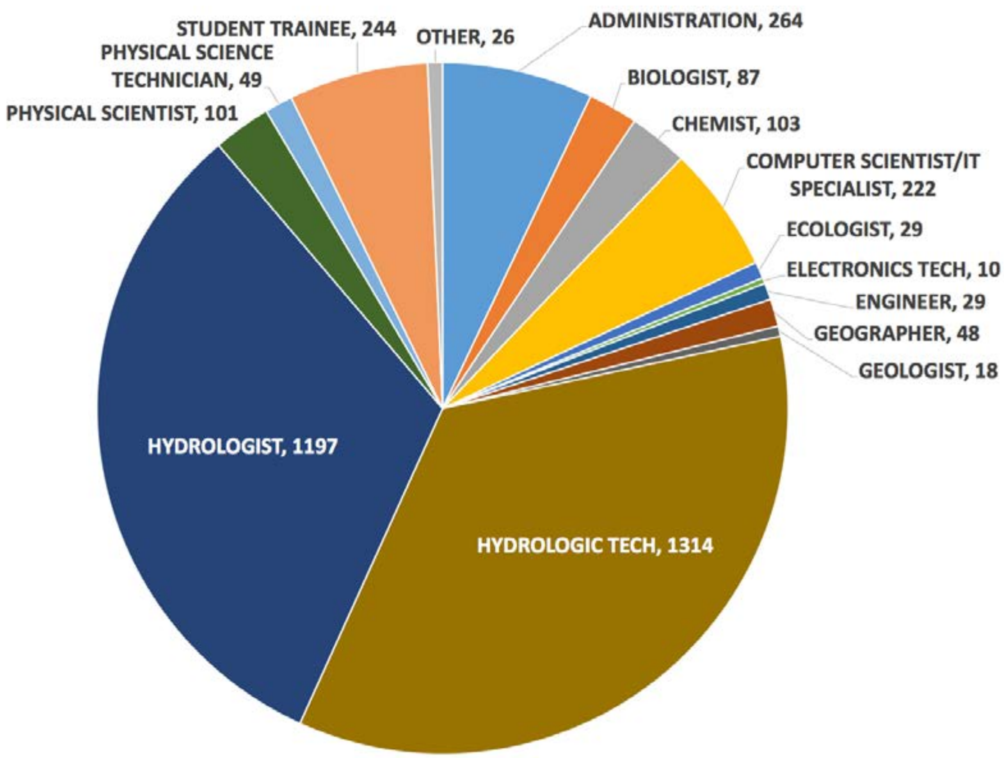

Figure A.1 USGS WMA workforce. SOURCE: Dr. Don Cline, USGS associate director for water; as presented to the committee on September 18, 2017.

WMA personnel respond to strategic national priorities set by headquarters as well as regional, state, and local needs determined largely by collaborative partners. WMA maintains a physical presence across the nation, with facilities in each state as well as in Puerto Rico, the U.S. Virgin Islands, and the U.S.-affiliated Pacific Islands. Most scientific work is managed through state or regional WSCs. Science support for these centers comes from a series of USGS laboratory and technical facilities, such as the National Water Quality Laboratory in Lakewood, Colorado, and the Hydrologic Instrumentation Facility at the Stennis Space Center in Mississippi. These facilities help USGS personnel and cooperators conduct studies and analyze water quantity and quality issues throughout the nation, its territories and the U.S.-associated Pacific Islands by providing broad analytical services, assisting in processing samples, providing instrumentation and training for deployment and maintenance of sensors, as well as processing data and making them available to the public. This operational structure, partially determined by federal authority and through U.S. congressional appropriations, helps to foster interaction with state, regional, and local partners and ensures that USGS provides focused and relevant national scientific expertise to states and localities[5] (Brooks, 2001). This cooperation helps USGS maintain awareness of water science and resources challenges across the United States and ensures that national missions and goals remain aligned with emerging trends (Blanchard, 1999).[6]

[5] See https://water.usgs.gov/coop/about/CWP.science.priorities.pdf; accessed September 17, 2018.
[6] See https://water.usgs.gov/coop/about/CWP.briefing.sheet.pdf; accessed September 17, 2018.

As noted in Chapter 1, WMA's strategy is to provide water resource monitoring, assessment, modeling, and research data and tools that are relevant to:

- Preserving the quality and quantity of the nation's water resources;
- Balancing water quantity and quality in relation to potential conflicting uses;
- Understanding, predicting, and mitigating water-related hazards; and
- Quantifying the vulnerability of human populations and ecosystems to water shortages, surpluses, and degradation of water quality.

The 2013 *USGS Water Science Strategy* document (Evenson et al., 2013) reframes the above national objectives into five operational goals:

1. Provide society with the high-quality information it needs regarding the amount and quality of water in all components of the water cycle at high temporal and spatial resolution, nationwide.
2. Advance understanding of processes that determine water availability.
3. Predict changes in the quantity and quality of water resources in response to changing climate, population, land-use, and management scenarios.
4. Anticipate and respond to water-related emergencies and conflicts.
5. Deliver timely hydrologic data, analyses, and decision-support tools seamlessly across the nation to support water-resources decisions.[7]

WMA's various programs, subprograms, divisions, and WSCs work to achieve these five stated goals through *observing* the water cycle, improving *understanding* of critical processes, *predicting* changes in water availability and quality over time, and *delivering* water science data and information to the federal, state, and local agencies, the public, tribes, and industry to support informed decision-making. WMA activities related to each of the five goals are briefly summarized below. In addition, a sixth goal that relates to *cross-cutting issues* with other USGS mission areas is discussed.

WMA CAPABILITIES

Observing the Water Cycle

USGS water programs are perhaps best known for their long history of measuring and monitoring streamflows, surface-water and groundwater levels, and water quality. Through networks consisting of streamgages (some with continuous water-quality monitoring stations), precipitation stations, and groundwater observation wells, WMA attempts to quantify water availability and quality across the United States. At present, USGS has about 8,200 streamgages located across the country. Data collected at each site vary based on federal, state, and regional requirements. Additionally, USGS maintains 1,900 continuous water-quality sampling stations,

[7] Data provided to the committee by Dr. Don Cline, associate director for water, at the committee's first meeting on September 18, 2017.

with selected variables recorded every 15 minutes.[8] Local data collection intervals vary depending on site conditions. Temperature, conductance, pH, dissolved oxygen, turbidity, nitrates, and chlorophyll are some of the parameters measured.

USGS or its cooperators collect intermittent data from about 17,000 groundwater observation wells across the country. The actual number of wells can vary from year to year, based on access. About 1,800 of these provide real-time monitoring of water levels; these data are all considered as part of the active groundwater-level network.[9,10] About 1,000 of these wells provide daily water level measurements. The remainder of these observation well data are collected periodically, often by cooperators at state agencies. USGS awards up to $2 million annually[11] in cooperative agreements to support participation in the National Ground-Water Monitoring Network (NGWMN). Since this program began in 2015, 30 agencies have either completed the process of becoming a data provider to the network, have an ongoing project to become a data provider, or have a project to enhance NGWMN sites. USGS maintains about 250 precipitation-monitoring stations. Often these data are collected for local municipalities and help augment National Weather Service or U.S. Army Corps of Engineers (USACE) networks. The networks are maintained and operated through various programs funded through federal, state, and local agencies. For example, the vast majority of streamgages in the USGS network are funded jointly by USGS and state, regional, local, and tribal partners. These streamgages provide data beneficial to localities and therefore require matching funds by local partners. While a majority of streamgages are cooperatively funded, approximately 15 percent of U.S. streamgages are considered essential due to their importance in fulfilling various missions within USGS or meeting strategic long-term federal responsibilities within other agencies and are funded by USGS without joint cooperator funding under the Federal Priority Streamgages designation administered by the Groundwater and Streamflow Information Program (and its predecessor the National Streamflow Information Program) (DOI, 2018). While this designation applies to 3,460 streamgages, in 2017, only 1,176 gages were fully funded by USGS, while the remaining 2,284 were jointly funded by USGS and partners (DOI, 2018).

In addition to hydrologic and observational networks, USGS collaborates with various national research laboratories across the United States in various programs, including those at USGS facilities such as the National Water Quality Laboratory and the Hydrologic Instrumentation Facility. Numerous state and regional agencies and universities are engaged as collaborators to facilitate monitoring, consistent data collection, and quality assurance procedures. The USGS National Water-Use Science Project (formerly the National Water-Use Information Program) assembles and distributes water-use data. This program, using data primarily supplied by states and cooperators, analyzes the sources, uses, and fate of water at local, state, and national scales, documents water-use trends, and prepares national water-use summaries on a 5-year basis. These data are organized by water use categories. A related research program, the National Water Census, develops analytical tools and explores links between water use and water quality. This program distributes watershed- and county-based water budget data online through the National Water Census Data Portal.

---

[8] Data provided by Dr. Don Cline and Robert Moore, USGS WMA.
[9] Data provided by Dr. Don Cline and Robert Moore, USGS WMA.
[10] See https://groundwaterwatch.usgs.gov/default.asp; accessed September 17, 2018.
[11] See https://www.usgs.gov/news/usgs-seeks-national-ground-water-monitoring-network-proposals-2018; accessed July 30, 2018.

USGS observations involve all aspects of the water cycle. WMA personnel develop, evaluate, and apply new measurement and characterization techniques for gathering water resource information. Airborne, surface, and borehole geophysical techniques help characterize subsurface geology and aquifer geometry to enhance groundwater studies. Chemical and isotopic tracing and fingerprinting techniques are being applied to water quality and biogeochemical investigations. Innovative equipment and sensors are used to monitor surface water flows and quality.

Understanding Critical Processes

WMA advances understanding of processes affecting water quality and availability throughout the water cycle to inform decision making through its own research and through collaborations with federal and nonfederal partners as well as through the administration of grants. Active research activities include investigations of the water cycle, hydrodynamics, hydrological-ecological interactions, water resources availability, and hydrogeophysics. Many of these investigations are carried out in WSCs through the USGS Cooperative Matching Funds (Coop) Program.

One of the most important programs to WMA, the Coop Program, supports applied science through collaboration between WSCs and non-federal agencies within each state. Under the Coop Program, federal funds are matched by nearly 1,600 local, municipal, county, state, regional, and tribal partners to conduct water science and research activities across the United States and its territories and protectorates. This state and local funding represents more than 50 percent of the $314 million reimbursable budget of the WMA (see Figure A.2), a large percentage of the total FY2017 $529 million budget, and has become a major driver of USGS programming.[12] By using consistent procedures and standards, WMA ensures that data collected from the Coop Program are consistent across all of the regions and available within USGS databases for use at local, state, regional, and national scales. These collaborations help keep the work of WMA focused on practical needs of each county, state, and regional partner, while informing and providing visibility to emerging issues. A majority of the streamgages in the network are funded through the Coop Program.[13] Likewise, the program helps manage data from networks of groundwater monitoring wells in most states.

In most WSCs, the Coop Program supports multiple applied water science projects under the broad umbrella of understanding the water cycle. These studies are usually focused on local or regional needs and often have significant field components. Projects range in scope from large and long term, such as integrated eco-hydrologic assessments of the California Bay Delta system (Mueller-Solger, personal communication[14]), to smaller and short term, such as an evaluation of the water supply for a state-run fish hatchery in Wisconsin (Dunning et al., 2017). The Coop Program allows cooperators to address local problems while tapping into national expertise, capabilities, and equipment that might not otherwise be available. The program also keeps the regional and local WSCs in touch with local and regional issues and fosters beneficial technology transfer between USGS scientists and local experts.

---

[12] Data provided to the committee by Dr. Don Cline, associate director for water, at the committee's first meeting on September 18, 2017.
[13] See https://water.usgs.gov/coop/about/monitors.html; accessed September 17, 2018.
[14] Communication during committee's open session in San Diego, California, on November 30, 2017, with Anke Mueller-Solger, U.S. Geological Survey.

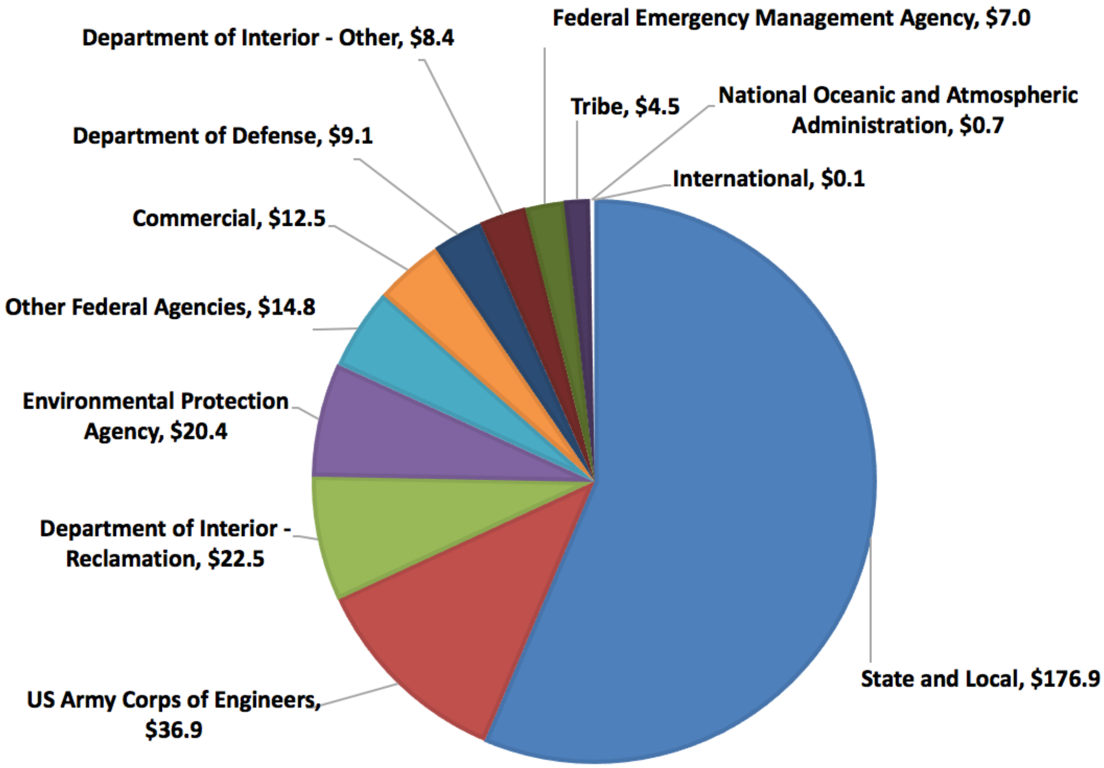

Figure A.2 Breakdown of total FY 2017 reimbursable funds from WMA partners, totaling $314 million. SOURCE: Dr. Don Cline, USGS associate director for water; as presented to the committee on September 18, 2017.

An important connection between USGS water programs and university water science programs is through the National Institutes for Water Resources. There are 54 water resources research institutes, which were established through the Water Resources Research Act of 1964 and are generally co-located within land-grant universities across the United States and its territories.[15] The water resources research institutes distribute annual base grants, coordination grants, and national competitive grants, as well as student internship opportunities. Coordinated by USGS through the National Institutes for Water Resources, these institutes have historically received modest base funding from WMA, which is then leveraged significantly by the universities, and through extramural grants obtained by university scientists and students through the State Water Research Grant Program; while the National Water Research Grants Program funds research of national importance.[16] The institutes serve as local hubs for promoting technology and information transfer between university and USGS scientists, and the academic connections are critical for helping train the next generation of water scientists and engineers, some of whom go on to have careers within USGS.

In addition to the Coop Program, WSCs, and the National Institutes for Water Resources, WMA collaborates extensively with federal agencies on a wide variety of national projects and science related activities. From collaboration with the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service on data related to flood forecasts,

[15] See https://water.usgs.gov/wrri/index.php; accessed September 17, 2018.
[16] See https://water.usgs.gov/wrri/2014-NIWR-USGS-Fact-Sheet.pdf; accessed September 17, 2018.

coordination with the Federal Emergency Management Agency (FEMA) on disaster response or making data readily available for use by other agencies, USGS works extensively to assist federal agencies. These collaborations provide reimbursable income to USGS, helping to sustain its programs and workforce beyond its own federal appropriations. While many examples can be cited, a few are provided for context. In a major collaborative effort, USGS is working with NOAA and USACE to develop a National Water Model in a modeling-method integration effort to forecast streamflow over the continental United States in near real-time (see Box 2.1).[17] USGS is also leading the development of the subsurface hydrology model in the National Water Model. Similarly, USGS and the U.S. Environmental Protection Agency (EPA) collaborated to develop a new surface-water modeling tool, called the Surface Water Toolbox, designed to be of particular use to regulators and watershed managers. It combines USGS's Surface-Water Statistics software, used to enable statistical analysis of water time-series data, with the EPA's DFLOW tool, used for estimating streamflows for low-flow analysis and water quality standards. USGS research and partnerships with federal, state, and local collaborators provides innumerable benefits to USGS, its cooperators, and the nation. These investigations improve understanding of processes surrounding water quantity and quality and inform decisionmakers while providing publicly accessible data.

Predicting Changes in Water Availability and Quality

One of the most critical components of the work of USGS is to provide data, information and tools for predicting long- and short-term changes to the water cycle for federal, state, regional, tribal, and local stakeholders and managers. Data and observations are transferred in publications, usable data science products, Web communications, and decision-support tools, which serve as important resources for water managers and policymakers for predicting future outcomes. USGS has developed numerous hydrologic and geochemical simulation models that are used to predict changes in hydrologic systems of given various stresses, and these products are useful in determining potential water quantity and quality impacts to surface and groundwater.

While numerous USGS models exist, three examples that are important to water resources managers and scientists are the SPARROW (Spatially Referenced Regressions on Watershed attributes) models, MODFLOW models, and the National Hydrologic Model. SPARROW models provide statistical estimates about the origin, transportation, and fate of nutrients and contaminants moving through watersheds, linking monitoring data to watershed hydrology.[18] These models help managers determine how to reduce contaminant loads, predict water quality changes, design management strategies, and change policies. Similarly, the MODFLOW family of groundwater flow codes allows simulation and prediction of groundwater conditions as well as groundwater–surface water interactions.[19] USGS also leads integrative modeling efforts, such as the National Hydrologic Model, in addition to providing foundational support to the development of the National Water Model led by the National Weather Service (see Box 2.1). The National Hydrologic Model couples the USGS Precipitation-Runoff Modeling System with MODFLOW to create integrated surface water–groundwater models over nested Hydrologic Response Units across the nation (Regan et al., 2018). It is supported by the USGS National Geospatial Data Portal and provides to the public calibrated model parameters, readily usable by local, state, and regional

[17] See http://water.noaa.gov/about/nwm; accessed September 17, 2018.
[18] See https://water.usgs.gov/nawqa/sparrow; accessed September 17, 2018.
[19] See https://water.usgs.gov/ogw/modflow; accessed September 17, 2018.

water managers. Such tools provide invaluable resources for the private and public sectors to use USGS data and science to make informed decisions about water resources.

Delivering Water Science Data and Information

USGS is known for long-term storage of historical water data and for delivery of real-time data. WMA is responsible for data collection, quality assurance, and dissemination of data and information on water activities across the United States. USGS collects large amounts of data on the water cycle, generally within the broad categories of surface water and groundwater. “Super” gages (also known as “sentry” gages), which represent a small subset of streamgages, can measure data such as temperature, specific conductance, pH, nutrients (e.g., nitrogen, phosphorous), and sediment concentration (Shoda et al., 2015). Such continuous water-quality gages allow USGS to monitor streamflow conditions under average conditions as well as under storm or accidental spill situations. Data on pesticides, emerging contaminants, and volatile organic compounds are collected as part of the National Water-Quality Assessment (NAWQA) program. In addition to critical data collection around surface water and groundwater quantity and quality, WMA provides information on flood inundation; acid rain, atmospheric deposition, and precipitation; chemistry; biological communities and physical habitat; reservoir sedimentation; and water-use data.

Much of these data are accessible through the National Water Information System (NWIS) database containing water data collected at more than 1.5 million sites around the United States and at some border and territorial sites.[20] These data provide opportunities to view changes in water availability and quality overtime. NWIS stores numerous types of data; however, local WSCs may need to be contacted to obtain some information. In 2017, USGS real-time water data was requested 120 million times per month.[21] In addition to the NWIS, WMA houses relevant data through various sites, such as Water Watch,[22] Water Quality Watch,[23] Groundwater Watch,[24] and WaterNow.[25] Numerous other sites accessible through the WMA website allow academics, scientists, managers, and other users to readily access data for use in academic and scientific study, emergency management, and decision-making. The processes of data acquisition, storage, and delivery are constantly evolving as instrumentation and sensors now collect more data more rapidly than ever before and as stakeholders demand real-time, open-source data delivered. Consequently, the NWIS system has evolved from a relatively static database in the 1970s to a constantly updated real-time delivery system today (see Figure A.3). Understanding, interpreting, and delivering this vast data collection has included advances in data informatics and data visualization, which represent new frontiers for WMA.

[20] See https://waterdata.usgs.gov/nwis; accessed September 17, 2018.
[21] Communication during committee’s open session in San Diego, California, on November 30, 2017, with Dianna Crilley, U.S. Geological Survey.
[22] See https://waterwatch.usgs.gov/index.php; accessed September 17, 2018.
[23] See https://waterwatch.usgs.gov/wqwatch; accessed September 17, 2018.
[24] See https://groundwaterwatch.usgs.gov; accessed September 17, 2018.
[25] See https://water.usgs.gov/waternow; accessed September 17, 2018.

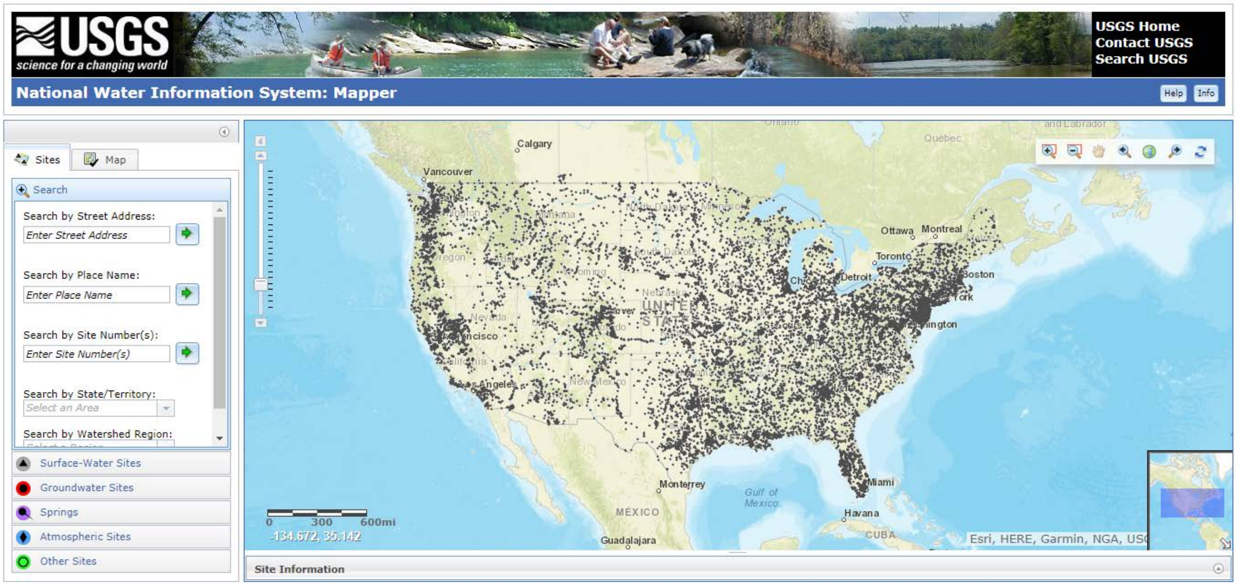

Figure A.3 Splash page for USGS's National Water Information System. The page allows users to select various USGS monitoring sites across the United States and access data such as streamflow, discharge, and field measurements at selected locations. SOURCE: https://maps.waterdata.usgs.gov/mapper/index.html, accessed September 6, 2018.

Cross-Cutting Science with Other USGS Mission Areas

Because water science is a fundamental part of most Earth system studies, WMA programs and activities are substantially linked to the work of other USGS mission areas (Evenson et al., 2013). These crosscutting links include:

- **Core Science Systems**, which focuses on advances in modeling, data acquisition and manipulation, visualization tools, and advances in Earth-science data collection such as lidar, the National Hydrography Dataset, and remote sensing;
- **Ecosystems**, linking water resources to ecosystem health and stability;
- **Energy and Minerals**, exploring relationships between water-resources questions and the energy cycle and the nation's mineral resources;
- **Environmental Health Science**, coordinating research on water resources related to human health, emerging contaminants, pathogens in the environment, and related issues;
- **Land Resources**, in which WMA has roles in the National Water Census, predicting future changes in floods and droughts, and long-term assessments of changing water quality through the NAWQA program; and
- **Natural Hazards**, in which WMA has important roles in helping protect the safety, security, and well-being of the nation by collecting data and carrying out research related to flooding, landslides, erosion, debris flows, and other hazards.

STAKEHOLDER ENGAGEMENT

Over the course of this study, the committee heard input from numerous USGS cooperators, stakeholders, collaborators, and data users, which included federal and state agency staff, state geological surveys, university and laboratory researchers, and nongovernmental organizations (see Appendix B for a list of presenters and attendees of information-gathering sessions). While USGS cooperators and data users expressed many opinions relevant to their regional or local needs, a majority commended USGS for its extensive hydrologic monitoring network, stdakeholder collaborations with USGS scientists on numerous investigations, and much of the cooperative work that WMA does with local, state, and regional agencies. Overwhelmingly, state and nongovernmental stakeholders praised USGS for the streamgage network and its critical importance not just federally, but for localities, states, and regions. These stakeholders encouraged USGS to continue to strategically maintain or expand this network, when feasible.

Federal Engagement

Numerous federal stakeholders repeatedly stated the importance of data sets maintained by USGS and the importance of this information as a foundation for their own programs, decision-making, and disaster and emergency response efforts. Federal staff across various agencies (e.g., EPA, FEMA, NOAA, U.S. Department of the Interior [DOI], USACE) stated the need to ensure the integrity and continuity of these data to better inform their own decision-making. For example, USGS provides water-use accounting data to the U.S. Bureau of Reclamation for dam releases, provides water-quality assistance to tribes, and provides a more informed understanding of land-use change across the United States. The streamgage network, storm-surge sensors, and hydrographic maps provide federal agencies within DOI with the ability to manage river and aquifer basins and to respond to emergencies.

Elsewhere within the federal government, staff value the collaborations with USGS on model development with agencies (i.e., EPA, the National Aeronautics and Space Administration [NASA], NOAA, the U.S. Department of Energy), data for water releases with USACE, and emergency response with FEMA. Decision makers reiterated a continued need to look to USGS to answer science questions regarding the decision-making tradeoffs that are implicit in water decision making, such as mid- and long-range water prediction capabilities and the development of new hydrologic models. Stakeholders urged USGS to increase its spatial and temporal coverage of the hydrologic network to improve decision-making.

State-Level Engagement

At the state level, stakeholders noted USGS's hydrologic monitoring network and data sets and reiterated their continued need for basic water-data collection facilitated by USGS. Similar to numerous federal staff, state agency staff value existing USGS data sets and expressed interest in expansion of the existing monitoring networks. The committee heard from a number of state agency representatives about issues that impact their ability to work with USGS, including cooperator limitations, a concern about base funding for the streamgage network, and a perceived pressure that USGS needs to work on any project with funding, whether within its purview or not. There was also a sense that USGS could improve identification of roles and partnerships with other federal agencies.

Other Stakeholders

The committee heard input from numerous local and regional stakeholders who interact with USGS in a variety of capacities. These stakeholders suggested that USGS focus on the core competencies of:

1. Hydrologic data collection and the methods development that the data collection entails;
2. Conversion of data into useful information;
3. Long-term studies of hydrologic processes; and
4. Development and application of models to gain insight into processes and to evaluate past or potential scenarios.

The academic community expressed support for USGS and its collaborations with the community through interactions on scientific research. A number of stakeholders believe the USGS does an effective job within the public–private partnership realm. These interactions have increased the understanding within the field and also brought in external funding for research topics. However, there is concern that funding pressures could lead to the removal of monitoring networks in smaller watersheds, despite their importance to long-term land use change in larger basins. Other stakeholders expressed a desire for USGS to decrease the amount of time to process and make data publicly available. Stakeholders at all levels encouraged USGS to work to improve model integration between surface water and groundwater, emphasizing how beneficial this would be in their own work.

B

Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

George M. Hornberger (NAE), *Chair*, 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. Previously, he was a professor at the University of Virginia, where he held the Ernest H. Ern Chair of Environmental Sciences. He has been a visiting scholar at the Australian National University, Lancaster University, Stanford University, the University of California, Berkeley, the University of Colorado, and the U.S. Geological Survey (USGS). His research is aimed at understanding complex water-energy-climate interrelationships. Dr. Hornberger is a fellow of the American Geophysical Union (AGU), the Association for Women in Science, and the Geological Society of America. He has served on numerous boards and committees of the National Academies of Sciences, Engineering, and Medicine, including as chair of the Commission on Geosciences, Environment, and Resources (1996–2000); chair of the Board on Earth Sciences and Resources (2003–2009); and chair of the Water Science and Technology Board (2013–2017). Dr. Hornberger was elected a member of the National Academy of Engineering in 1996. He holds a B.S. in civil engineering, an M.S. in hydrology from Drexel University, and a Ph.D. in hydrology from Stanford University.

Kenneth R. Bradbury is Wisconsin state geologist and the director of the Wisconsin Geological and Natural History Survey, University of Wisconsin–Extension. Previously, Dr. Bradbury held various roles within the Survey, including research hydrogeologist and professor, Water and Environment program leader, and assistant director for science. He also holds an affiliate faculty appointment at the University of Wisconsin–Madison's Department of Geoscience. Dr. Bradbury's recent research has focused on developing regional groundwater flow models for groundwater and surface-water management. Additional research interests include investigating the movement of viruses in groundwater systems, characterizing and simulating fractured aquifers, determining groundwater flow paths near water-supply wells, wellhead protection, groundwater recharge, and the regional hydrogeology of Wisconsin. Dr. Bradbury holds a B.A. in geology from Ohio Wesleyan University, an M.A. in geology from Indiana University, and a Ph.D. in hydrogeology from the University of Wisconsin–Madison.

Yu-Ping Chin is professor of civil and environmental engineering at the University of Delaware. Prior to coming to Delaware, he was professor of Earth sciences at The Ohio State University for 26 years. He has also been a visiting research scientist at the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) in Switzerland and in the chemistry department at the University of Otago in New Zealand. Dr. Chin conducts research on the fate of synthetic organic chemicals in aquatic systems in both natural and the built environment. He is predominantly interested in the transformation of these compounds mediated by dissolved organic matter (DOM) in the presence of sunlight and under anaerobic conditions. He has conducted research on DOM-mediated biogeochemical processes in both the Arctic and the Antarctic. Dr. Chin served two terms as a member of the National Academies Water Science and Technology Board. He has also been a member on past National Academies' committees, including a Review of the WATERS Network Science Plan and Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites. Dr. Chin received his A.B. in geology from Columbia University in 1981 and a Ph.D. in civil and environmental engineering (Aquatic Chemistry) from the University of Michigan in 1988. He received further postdoctoral training at the Ralph M. Parsons Laboratory at the Massachusetts Institute of Technology from 1988 to 1991.

Ellen Gilinsky is president of Ellen Gilinsky, LLC. Prior to this role, she was an associate deputy assistant administrator and senior policy adviser in the Office of Water at the U.S. Environmental Protection Agency (EPA). In this position, she addressed policy and technical issues related to all EPA water programs with an emphasis on science, water quality, and state programs, including nutrient pollution, floodplain management, and harmful algal blooms. Prior to that appointment, she served as the director of the Water Division at the Virginia Department of Environmental Quality (DEQ) and at DEQ as the manager of the Office of Wetlands and Water Protection. She is a past president of the Association of Clean Water Administrators, has held a gubernatorial appointment to the state advisory board of the Virginia Water Resources Research Center, and served as an adjunct faculty member at Virginia Commonwealth University in the departments of biology and environmental studies. Dr. Gilinsky has 12 years of experience as an environmental consultant on water issues. She holds a B.A. in biology from the University of Pennsylvania and a Ph.D. in zoology from the University of North Carolina at Chapel Hill.

Peter H. Gleick (NAS) is president emeritus and chief scientist of the Pacific Institute for Studies in Development, Environment, and Security. Dr. Gleick is a world-renowned expert, innovator, and communicator on water and climate issues. In 1987, he co-founded the Pacific Institute, which he led as president until 2016 when he became chief scientist. Dr. Gleick was the first to successfully link general circulation models with regional hydrological models to characterize regional impacts of climate change on water. His subsequent work has focused on the challenges of providing basic human needs for water across the globe and understanding the interactions of global freshwater resources with respect to human environmental impacts, economic development, and international security. Notably, he also pioneered and advanced the concepts of the "soft path for water" and "peak water." Dr. Gleick received a MacArthur Fellowship and is a member of the National Academy of Sciences. Dr. Gleick holds a B.S. in engineering and applied science from Yale University and an M.S. and a Ph.D. in energy and resources from the University of California, Berkeley.

Robert E. Mace is associate director and chief water policy officer at The Meadows Center for Water and the Environment and professor of practice in the department of geography at Texas Tech University. Prior to his current position, he was a deputy executive administrator at the Texas Water Development Board (TWDB). There, he managed the Water Science and Conservation Program that studies the rivers and aquifers of the state, promoted the conservation of the state's water, and pursued innovative technologies such as desalination, rainwater collection, and water reuse. Previously, he was the division director for groundwater resources at TWDB. Dr. Mace also worked for nine years at the Bureau of Economic Geology at The University of Texas at Austin as a hydrologist and research scientist. During that time, he undertook research on groundwater modeling and hydrogeologic characterization of aquifers. Dr. Mace's expertise includes hydrogeology, water conservation, geostatistics, policy and science, and stakeholder processes and communication. He has more than 25 years of experience working with water in Texas. He holds a B.S. in geophysics and an M.S. in hydrology from the New Mexico Institute of Mining and Technology, and a Ph.D. in hydrogeology from The University of Texas at Austin.

Anne W. Nolin is professor of geography in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University (OSU). Prior to her appointment at OSU, Dr. Nolin was a research scientist at the National Snow and Ice Data Center, which is part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder. Her research focuses on mountain hydroclimatology, water scarcity, radiative transfer modeling, glaciers, meltwater, mountains as social-ecological systems, and remote sensing. She is a member of the National Aeronautics and Space Administration's (NASA's) Multi-angle Imaging SpectroRadiometer (MISR) Science Team and the NASA SnowEx Science Definition Team. She served as vice chair of the Water Resources and Global Hydrologic Cycle panel for the 2007 Earth Science and Applications from Space Decadal Survey and subsequently on the National Academies' Space Studies Board and Committee on Earth Sciences. She also currently serves on the NASA Earth Science Advisory Committee. Dr. Nolin was elected and served 3 years as the chair of the Cryosphere Focus Group of the American Geophysical Union. She holds a B.A. in anthropology and an M.S. in soils, water, and engineering from the University of Arizona, and a Ph.D. in geography also from the University of California, Santa Barbara.

Roger K. Patterson is assistant general manager for the Metropolitan Water District of Southern California, overseeing Metropolitan's strategic water initiatives for the Colorado River and Sacramento–San Joaquin Bay Delta. Mr. Patterson was the director of the Nebraska Department of Natural Resources from 1999 to 2005. He was responsible for water administration, water planning, floodplain delineation, dam safety, and the state databank. He represented Nebraska on interstate compacts, decrees, and basin associations and led the state team in the settlement of U.S. Supreme Court cases on the North Platte and Republican Rivers. Prior to his work in Nebraska, Mr. Patterson served 25 years with the U.S. Bureau of Reclamation. During his tenure there, he served as regional director in both the mid-Pacific region based in Sacramento and the Great Plains region headquartered in Billings, Montana. He is a registered professional engineer in Nebraska and Colorado. He has participated in several National Academies studies in the past, including the Committee on the Assessment of Water Resources Research. He holds B.S. and M.S. degrees in engineering from the University of Nebraska.

Ying Fan Reinfelder is professor in the Department of Earth and Planetary Sciences at Rutgers University. Her research interests include the global water cycle and its role in regulating global environmental change through time, in particular water-plant relations below ground, and the coevolution of land plants and the terrestrial environment. She was on the board of directors for the Consortium of Universities for Advancement of Hydrologic Sciences, Inc. (CUAHSI), and is on the NASA Earth Science Advisory Committee. She holds a B.S. in engineering from the Beijing Institute of Civil Engineering, an M.S. in geography from the University of Utah, and a Ph.D. in civil and environmental engineering from Utah State University.

Jennifer L. Tank is director of the Notre Dame Environmental Change Initiative and the Ludmilla F., Stephen J., and Robert T. Galla Professor of Biological Sciences at the University of Notre Dame. Dr. Tank's research focuses on the influence of human activities on ecosystem function in streams and rivers. Currently, much of Dr. Tank's research takes place in the agricultural Midwest, where she and her team focus on innovative techniques to improve sustainable agriculture by working with farmers to minimize negative effects on freshwater and livelihoods downstream. Dr. Tank currently leads the Indiana Watershed Initiative funded through the U.S. Department of Agriculture (USDA) Resource Conservation Partnership Program, which includes partnerships with The Nature Conservancy, local Soil and Water Conservation Districts, county surveyors, and the USDA Natural Resource Conservation Service. Her goal is to improve the health and nutrient removal efficiency of streams and rivers draining cropland in the agricultural Midwest through implementation of watershed-scale conservation using real-time nutrient sensing, cover crops, and novel drainage management. She was a 2013 Leopold Leadership Fellow. Dr. Tank holds a B.S. in zoology from Michigan State University and an M.S. and a Ph.D. in ecology from Virginia Tech.

Howard S. Wheater is the Canada Excellence Research Chair Laureate in Water Security at the University of Saskatchewan and a Distinguished Research Fellow and Emeritus Professor of Hydrology at Imperial College London. A leading expert in hydrological science and modeling, he has published more than 200 refereed articles and six books. He is a Fellow of the Royal Society of Canada, the Royal Academy of Engineering, and the American Geophysical Union and a winner of the Prince Sultan bin Abdulaziz International Prize for Water and the World Meteorological Organization/United Nations Educational, Scientific and Cultural Organization (UNESCO)/International Association of Hydrological Sciences International Hydrology Prize (Dooge Medal). He has initiated and led national and international research programs in the United Kingdom and Canada and founded the Global Institute for Water Security at the University of Saskatchewan and the pan-Canadian Global Water Futures program. He has advised states, provinces, and national governments on flood, water resources, and water quality issues. He represented Hungary and Argentina at the International Court of Justice, sat on an International Court of Arbitration concerning the Indus Waters Treaty, and is currently an expert advisor to the government of Chile in a case before the International Court of Justice. He was, until 2014, vice chair of the World Climate Research Programme's Global Energy and Water Cycle Exchanges project and leads UNESCO's Global Network on Water and Development Information for Arid Lands program. His role as chair of the Council of Canadian Academies Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada saw the release of a report in February 2013 titled *Water and Agriculture in Canada: Towards Sustainable Management of Water Resources*. He holds B.A. and M.A. degrees in engineering science from the University of Cambridge and a Ph.D. in civil engineering and hydrology from the University of Bristol.

STAFF

David M. Allen (*Co-Study Director*) is a senior program officer for the National Academies' Board on Atmospheric Sciences and Climate (BASC). From 2003 to 2015, Mr. Allen worked at the U.S. Global Change Research Program (USGCRP) Office, where he focused on international global change research and international assessment. In this role, he developed and maintained a comprehensive international portfolio for USGCRP. Examples of from this portfolio include obtaining national funding for international research programs (e.g., World Climate Research Programme, Future Earth), recruiting and conducting national reviews of international assessments (e.g., Intergovernmental Panel on Climate Change, World Ocean Assessment), coordinating an interagency international working group, coordinating funding for regional global change research and capacity-building organizations (e.g., Inter-American Institute for Global Change Research, Asia-Pacific Network for Global Change Research, the SyTem for Analysis, Research, and Training). Mr. Allen received his B.A. in sociology and pre-medical sciences from the University of Massachusetts at Boston and an M.S. in biological oceanography from the University of Washington.

Deborah Glickson (*Co-Study Director*) is a senior program officer with the Board on Earth Sciences and Resources at the National Academies. She received an M.S. in geology from Vanderbilt University and a Ph.D. in oceanography from the University of Washington. Her doctoral research focused on magmatic and tectonic contributions to mid-ocean ridge evolution and hydrothermal activity at the Endeavour Segment of the Juan de Fuca Ridge. After completing her Ph.D., she participated in the Dean John A. Knauss Marine Policy Fellowship and worked on coastal and ocean policy and legislation in the U.S. Senate. She joined the National Academies' Ocean Studies Board in 2008 and has worked on many ocean and Earth science studies with topics including ocean science research and infrastructure, coastal zone dynamics, marine hydrokinetic energy, methane hydrates, coal mining and human health, and geoscience education. Dr. Glickson was also the associate director of the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Ocean Exploration, Research, and Technology at Florida Atlantic University–Harbor Branch Oceanographic Institute from 2015 to 2016.

Brendan R. McGovern is a research assistant with the National Academies' Water Science and Technology Board. Mr. McGovern has contributed to several studies and activities, on topics such as municipal water supply, aquifer storage and recovery, community-based flood insurance, ecosystem restoration, and coastal risk reduction. He previously worked and interned with the American Association for the Advancement of Science and the Stimson Center on international water security issues. He earned his B.A. degrees in political science and history from the University of California, Davis.

Carly Brody is a senior program assistant for the National Academies' Water Science and Technology Board and the Board on Earth Sciences and Resources. She received a B.A. degree in environmental science and policy and American studies at the University of Maryland, College Park. Prior to joining the National Academies in 2017, she interned with the Center for Transboundary Water Management at the Arava Institute for Environmental Studies.

C

People Who Provided Input to the Committee

Meeting 1: Washington, DC
September 18–19, 2017

Jennifer Saleem Arrigo, U.S. Global Change Research Program
Adrienne Bartlewitz, U.S. Geological Survey
Robert Bastian, U.S. Environmental Protection Agency
Don Cline, U.S. Geological Survey
Melinda Dalton, U.S. Geological Survey
Thomas Graziano, National Oceanic and Atmospheric Administration
William Guertal, U.S. Geological Survey
Bob Joseph, U.S. Geological Survey
Jack Kaye, National Aeronautics and Space Administration
David Lesmes, U.S. Department of Energy
Steve Moulton, U.S. Geological Survey
Hannah Paton, Center for Water Security and Cooperation
Kerry Rae, U.S. Department of the Interior
Jose Sanchez, U.S. Army Corps of Engineers
Michael Shapiro, U.S. Environmental Protection Agency
Nagy Zsolt, AECOM

Meeting 2: San Diego, California
November 30–December 1, 2017

Bill Alley, National Groundwater Association
Jerad Bales, Consortium of Universities for the Advancement of Hydrologic Science, Inc.
David Berger, U.S. Geological Survey, Nevada Water Science Center
Dianna Crilley, U.S. Geological Survey, California Water Science Center
Maurice Hall, Environmental Defense Fund
Joe Holomuzki, U.S. Geological Survey, Hydrological-Ecological Interactions Branch
Jeanine Jones, California Department of Water Resources
Matt Landon, California Water Science Center
Anke Mueller-Solger, U.S. Geological Survey, California Water Science Center
Steve Phillips, U.S. Geological Survey, California Water Science Center
Eric Reichard, U.S. Geological Survey, California Water Science Center
Julie Zimmerman, U.S. Geological Survey, The Nature Conservancy

Webinar I: Hydrological Observations
January 23, 2018

Deb Agarwal, Lawrence Berkeley National Laboratory
Dermott Diamond, Dublin City University
Barbara Minsker, Southern Methodist University

Webinar II: Stakeholders and Nongovernmental Organizations
January 26, 2018

Carlton Haywood, Interstate Commission on the Potomac River Basin
Eric Kuhn, Colorado River District
Beth McGee, Chesapeake Bay Foundation

Meeting 3, Chicago, Illinois
February 8–9, 2018

Amy Beussink, U.S. Geological Survey, Illinois-Iowa-Missouri Water Science Center
Nate Booth, U.S. Geological Survey, Data Science Branch
Joe Brammeier, Alliance for the Great Lakes
Steve Cole, Great Lakes Commission
Jeff Frey, Indiana Department of Environmental Management
Ken Najjar, Delaware River Basin Commission
Jason Navota, Chicago Metropolitan Agency for Planning
Bob Newport, Metropolitan Planning Council
J. David Rankin, Great Lakes Protection Fund
Jordan Read, U.S. Geological Survey, Data Science Branch
Bill Schleizer, Delta Institute
John Selker, Oregon State University

Water Science Center Directors Questionnaire Respondents

William Andrews, U.S. Geological Survey, Oklahoma Water Science Center
Cynthia Barton, U.S. Geological Survey, Washington Water Science Center
David Berger, U.S. Geological Survey, Nevada Water Science Center
Kyle Blasch, U.S. Geological Survey, Idaho Water Science Center
John Bumgarner, U.S. Geological Survey, New Mexico Water Science Center
Jeff Conaway, U.S. Geological Survey, Alaska Water Science Center
James Crammond, U.S. Geological Survey, Oregon Water Science Center
Mary Foley, U.S. Geological Survey, Maryland-Delaware-DC Water Science Center
Mike Griffin, U.S. Geological Survey, Ohio-Kentucky-Indiana Water Science Center
John Kilpatrick, U.S. Geological Survey, Montana-Wyoming Water Science Center
James Leenhouts, U.S. Geological Survey, Arizona Water Science Center

Keith Robinson, U.S. Geological Survey, New England Water Science Center
Eric Strom, U.S. Geological Survey, South Atlantic Water Science Center
Robert Swanson, U.S. Geological Survey, Nebraska Water Science Center
JoyceWate Williamson, U.S. Geological Survey, Dakota Water Science Center
Andrew Ziegler, U.S. Geological Survey, Kansas Water Science Center

Association of American State Geologists Meeting Participants and Questionnaire Respondents

Mike Angle, Ohio Geological Survey
Jonathan Arthur, Florida Geological Survey
Richard Berg, Illinois State Geological Survey
Karen Berry, Colorado Geological Survey
Gale Blackmer, Pennsylvania Geological Survey
Mitch Blake, West Virginia Geological and Economic Survey
Jeremy Boak, Oklahoma Geological Survey
Erin Campbell, Wyoming State Geological Survey
Marjorie Gale, Vermont Geological Survey
Joseph Gellici, South Carolina Geological Survey
Joe Gillman, Missouri Geological Survey
Jeffrey Hoffman, New Jersey Geological and Water Survey
Stephen Mabee, Massachusetts Geological Survey
Robert Marvinney, Maine Geological Survey
Steve Masterman, Alaska Division of Geological and Geophysical Surveys
John Metesh, Montana Geological Survey
Dave Norman, Washington Geological Survey
Richard Ortt, Maryland Geological Survey
John Parrish, California Geological Survey
Jonathan Price, Nevada Geological Survey
William Prior, Arizona Geological Survey
David Spears, Virginia Geological Survey
Kenneth Taylor, North Carolina Geological Survey
Margaret Thomas, Connecticut Geological Survey
Todd Thompson, Indiana Geological Survey
Harvey Thorleifson, Minnesota Geological Survey
Mike Timmons, New Mexico Geological Survey
David Wunsch, Delaware Geological Survey
John Yellich, Michigan Geological Survey
Ronald Zurawski, Tennessee Geological Survey

D

Prioritization Rubric

The committee developed the following rubric as a way to refine the water resource and science challenges and questions identified for the next 25 years (see Statement of Task 1 and Box 1.1) to those that would have high potential to benefit the U.S. Geological Survey's (USGS's) strategic science and other federal agency priorities (see Statement of Task 3). The rubric addressed scientific importance, societal need, relevance to the USGS mission, and relevance to partners; from these criteria, the committee was able to narrow the 10 questions identified in Chapter 2 of this report to the five in Chapter 3. This rubric was based on a project prioritization framework created by the Office of Quality Improvement at the University of Wisconsin–Madison.[1]

Criteria	Scoring Value	Priority Questions Identified in Chapter 3 of Report
Scientific Importance (global, national, regional, local)	• All four are high (4) • Three are high (3) • Two are high (2) • One is high (1)	
Societal Need (global, national, regional, local)	• All four are high (4) • Three are high (3) • Two are high (2) • One is high (1)	
Relevance to USGS Mission **Observes** **Understands** **Predicts** **Delivers**	• All four elements (4) • Three elements (3) • Two elements (2) • One element (1)	
Relevance to Partners **Other parts of USGS** **Other federal agencies** **State, tribal, and local agencies** **Stakeholders (nongovernmental organizations, general public, private sector)**	• All four partners (4) • Three partners (3) • Two partners (2) • One partner (1)	
Total Score:		

[1] Gosenheimer, C., B. Rust, and N. Thayer-Hart. 2012. *Project Prioritization: A Structured Approach to Working on What Matters Most. Office of Quality Improvement.* University of Wisconsin–Madison.