

Free Executive Summary

Integrating Multiscale Observations of U.S. Waters



Committee on Integrated Observations for Hydrologic and Related Sciences, National Research Council
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Summary

Water in the right quality and quantity, and at the right time, is essential to life—for humans and their food crops, and for ecosystems. Millions of people yearly die of water-related diseases; floods and droughts also cause illness and death in addition to economic damage throughout the world. Much of our agricultural activity would collapse in the absence of irrigation water. Natural ecosystems are adapted to stream discharge, precipitation, and evaporation patterns. Thus, future adjustments in the water cycle to climate, weather, and land-use change will undoubtedly have complex and significant impacts on the humans and other species that depend on it.

THE CHALLENGE OF UNDERSTANDING WATER FLOWS AND STORES

The management of water resources to meet these challenges will require improvements in our capacity to understand and quantify the hydrologic cycle and its spatial and temporal interactions with the natural and built environment. Just as in balancing a bank account, it is important to keep track of the amount of water in storage and the rates of inflow and outflow. Natural inflows to surface water bodies typically include precipitation, surface runoff, and groundwater inflow; outflows include evaporation, transpiration, and seepage into the ground. Natural inflow to ground water (recharge) results from the percolation of soil and other surface waters; outflows include transpiration and discharge to surface waters. Humans also withdraw from, and discharge to, surface- and groundwater.

There are two main challenges to understanding and quantifying the movement of water between and within stores and the associated changes in water constituents. First, many of the key processes, such as evaporation or movement of ground water within an aquifer, cannot be readily observed over large areas. Second, the rates of water movement can vary greatly in both space and time.

Three strategies are used individually or in combination to get around these problems, with varying degrees of success. First, when feasible, variables such as precipitation, river discharge, and wind speed are measured at specific locations (“point” measurements). Second,

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remote sensing methods can provide information on the spatial distribution of key variables. These methods measure over large areas, but the measurements represent averages over some space and time “window”. Remote sensing can be ground based (e.g., radar estimates of rainfall), or based on aircraft or satellites. Third, models are used to interpolate between point measurements (e.g., precipitation), estimate unmeasured quantities based on measured ones (e.g., chlorophyll concentrations from certain wavelengths of light, or evaporation from wind speed, temperature, and relative humidity) and to predict hydrological conditions under a hypothetical future combination of land use, land cover, and climate.

Even with these tools, the field suffers great limitations in many areas of measurement. For example, for most aquifers there are not accurate estimates of recharge, especially their spatial and temporal resolution. Likewise, accurate measurements of the spatial distribution of snow water storage are virtually impossible to make in many areas due to extreme topography and/or limited access.

THE PURPOSE OF THIS REPORT

Out of interest in these issues and their implications, in 2005 the National Research Council’s (NRC) Water Science and Technology Board (WSTB) formed the Committee on Integrated Observations for Hydrologic and Related Sciences to examine the potential for integrating new and existing spaceborne observations with complementary airborne and ground-based observations to gain holistic understanding of hydrologic and related biogeochemical and ecological processes and to help support water and related land-resource management. Funding for this effort (or for its parent standing committee, the Committee on Hydrologic Science [COHS]) was received from the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA), the Nuclear Regulatory Commission, and the Environmental Protection Agency (EPA). The full Statement of Task is shown in Box S-1. This report offers a comprehensive view of the current state of integrated observing for hydrology and the related sciences, with a particular emphasis on sensing.

OVERVIEW

The good news is that recent and potential future technological innovations offer unprecedented possibilities to improve our capacity to observe, understand, and manage hydrologic systems. Sensors are being developed that are smaller, less expensive, and require less power, allowing for deployment in much larger numbers. Researchers are designing sensors to provide previously unavailable information, such as real-time measurements of nutrient concentrations in surface, soil, or groundwater. Sensors are being arrayed in networks that enable the sharing of information and hence produce synergistic gains in observational capacity; these sensor networks offer the promise of filling critical gaps between traditional point and

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Box S-1
Statement of Task

This study will examine the potential for integrating new and existing spaceborne observations with complementary airborne and ground-based observations to gain holistic understanding of hydrologic and related biogeochemical and ecological processes and to help support water and related land-resource management. These systems are closely interconnected, and a great deal of common information is required in their study. The goal is to focus on information that would contribute to quantifying current and projected water availability, water quality and biogeochemical cycling, and land surface and related ecologic conditions. The assessment would consider these goals in the light of the capabilities of sensor and other in situ monitoring technologies and of spaceborne observation technologies. It would also look at likely advances in these technologies. The study will:

- (1) Identify processes in water flow and transport, related biogeochemical cycling, and ecological impacts where better information is needed to understand important mechanisms, how systems integrate at watershed and larger scales, and where new instrumentation or strategies for instrument placement could supply the needed data;
- (2) Identify contributions that observations obtained by remote sensing or other existing technology could make to understanding water flow and transport and related biogeochemical cycles as well as for addressing water management activities such as agricultural and municipal water supply, flood and drought prediction, water quality, and energy production;
- (3) Evaluate the readiness of the scientific and technical communities to make effective use of more precise and reliable observations of hydrologic fluxes and states (e.g., soil moisture, snow cover, carbon and nutrient transport, water bodies and wetlands, and water quality indicators);
- (4) Suggest research opportunities in these areas; and
- (5) Identify gaps in federal agency plans for integrating across sensors and products obtained from either in situ or space-based observations.

remotely sensed measurements. New sensors are being deployed on aircraft and satellites, and new ways are being thought of to use existing remote sensors. Computer models are being used to assimilate data from multiple sources to predict system behavior. And cyberinfrastructure initiatives are providing efficient and effective ways to share data with scientists, managers, and other potential users.

But there are gaps between the vision of what researchers and managers want to achieve and their ability to realize that vision. These gaps are real, but in many cases extremely narrow. Technical challenges include those associated with the development of robust, accurate, and affordable water quality sensors. All of the required technologies are expensive to develop, and most will at least initially require public funding until their commercial viability is established. Design and implementation of integrated hydrologic measurement systems requires the cooperation of diverse sets of researchers, technologists, and decision-makers. How can this cooperation be facilitated? Water management in the U.S. is typically local and rarely

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integrated. How can integrated hydrologic measurements provide greater benefit to local or regional decision-making?

A series of case studies was developed for the report, for regions as diverse as the Arctic, sub-Saharan Africa, and the Everglades, as well as the Great Plains, Mountain West, and coastal North Carolina of the United States.

- “Monitoring the Hydrology of the Everglades in South Florida” provides an example of a large, complex integrated observatory designed for pressing water management needs in an ecologically sensitive area.
- “Impacts of Agriculture on Water Resources: Tradeoffs between Water Quantity and Quality in the Southern High Plains” focuses on semiarid regions where water availability is a critical issue and where cycling of salts has large scale impacts on water quality.
- “Hydrological Observation Networks for Multi-Disciplinary Analysis: Water and Malaria in Sub-Saharan Africa” illustrates how observations can contribute to understanding and ameliorating major water-related public health problems.
- “Achieving Predictive Capabilities in Arctic Land-Surface Hydrology” explores a strategy for robust remote sensing hydrology in the pan-Arctic, to identify capabilities needed to link in-situ observations to satellite sensor scale observations.
- “Integrating Hydrologic Extremes and Water Quality in the Neuse River (North Carolina, USA) Basin and Estuary” focuses on the impact of human activity and hydroclimate variability on watershed nitrogen sources, cycling and export, and consequently on freshwater and estuarine ecosystem health.
- Finally, “Mountain Hydrology in the Western United States” discusses the need for high spatio-temporal resolution information on snow conditions due to sharp wet-dry seasonal transitions, complex topographic and landscape patterns, steep gradients in temperature and precipitation with elevation, and high interannual variability.

These case studies, taken in the context of discussions of sensors, networks, communications, data assimilation, and modeling, illustrate a number of important challenges regarding current and potential sensors and sensor networks, merging the resulting information with models, and providing useful products to managers and policymakers through traditional and emerging dissemination media. These challenges are presented below.

CHALLENGES

Development and Field Deployment of Land-Based Chemical and Biological Sensors

Physical sensors, such as those that measure air and water temperature and pressure, radiation, and wind speed and direction, are now mass produced and routinely packaged together in small instruments along with power and communication devices. However, sensor development for many important chemical and biological measurements is relatively immature.

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Development of a wide range of field-robust chemical and biological sensors is one of the greatest challenges facing widespread deployment of sensor networks in the hydrologic sciences.

Airborne Sensors

Airborne measurements operate at a spatial scale that fills the gap between the *in-situ* plot-scale observations and the larger satellite-scale observations. Airborne remote sensing at NASA historically was viewed as an intermediate step between initial sensor development and space deployment to help develop retrieval algorithms to validate new satellite sensors. It has not been viewed as a sensor program in its own right. This has impeded the development of operational airborne observing platforms that could play a very important role in hydrologic observations.

Space-borne Sensors

In satellite-based remote sensing, NASA has made good progress in developing and deploying sensors used primarily for research. Nonetheless, two challenges are relevant to this report: (1) a resolution of the “research-to-operations” transition from NASA-developed ‘experimental’ satellite observations to the broad variety of operational agencies and users that need routine (i.e., operational) observations, and (2) the lack of a corresponding monitoring strategy by entities such as EPA, USDA, NOAA, and state water and natural resources agencies that would incorporate airborne and/or satellite remote sensing measurements, where appropriate.

Bridging the Gap between Sensor Demonstration and Integrated Field Demonstration

There are significant inter-agency gaps between the steps of sensor development, sensor demonstration, integrated field demonstrations and operational deployment of sensors. The greatest gap is between sensor demonstration and integrated field demonstration. Closing this gap would involve integrating the sensor networks and webs within hydrologic observatories and experimental demonstration sites, and interfacing the sensor networks with the broader development of cyberinfrastructure.

Integrating Data and Models for Operational Use

The importance of data-model integration is apparent in a number of the case studies. For the Mountain Hydrology study, predictions of water availability are made from point measurements and model forecasts. In the Neuse River Basin study, management decisions are

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based on sparse water quality measurements. In each case, models and observations are used to guide management decisions, and in each case a data assimilation system that merges models and observations would offer improved predictions. The challenge is to develop methods that will be useful for broad families of applications, rather than just a few of the many possible applications.

The Next Step: Water Resource Applications

In the United States, large water resource problems involve multiple stakeholders, including government agencies, business interests, and the public. Management is typically diffuse, and standard measurement and modeling techniques and rules for water management are entrenched and often legally mandated. This produces a consistent dataset to show trends over time, and simplifies training and daily tasks of staff. However, it also leads to missed opportunities to improve the accuracy and precision of the data and resulting model predictions.

Funding Highly Interdisciplinary Science

Interdisciplinary science is increasingly common, but the design and use of integrated hydrologic measurement systems in specific research applications adds complexity to the challenge. These new kinds of projects will require unprecedented interdisciplinary cooperation among electrical engineers, computer scientists, modelers and the physical, chemical, and biological scientists who apply technology to hydrologic research. While many universities and research laboratories have the required expertise, marshalling this expertise on specific projects will likely require new programs or sources of funding.

Addressing the Fractured Federal Responsibility for Hydrologic Measurement, Monitoring and Modeling

The overarching barrier to the development and implementation of integrated hydrologic measurement systems is the lack of a single federal agency with primary responsibility for measuring, monitoring and modeling the environmental factors and processes that control the hydrologic cycle. It is easy to understand why the responsibility for measuring and monitoring the environmental factors and processes that control the hydrologic cycle might have evolved as it has. But the dual threats of global climate change and population growth demand a focused strategy for providing information on the nation's water resources and the environment.

The above challenges, along with the body of the report, lead to the recommendations of the study, which follow below.

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RECOMMENDATIONS

Recommendation 1

NSF, in partnership with NASA, NOAA, EPA, USGS, possibly national health and security agencies, and with collaboration from the private sector, should develop one or more programs that address the need for multi-disciplinary sensor development. An interagency sensor laboratory should be considered.

Recommendation 2

Serious consideration should be given to empowering an existing federal agency with the responsibility for integrated measurement, monitoring, and modeling of the hydrological, biogeochemical, and other ecosystem-related conditions and processes affecting our nation's water resources.

Recommendation 3

Coordinated and jointly funded opportunities for observatories, demonstration projects, test beds, and field campaigns should be significantly increased.

Recommendation 4

Agencies should consider offering new funding streams for projects at the scale of several million dollars per year for approximately 5-10 years to help close the gap between sensor demonstration and integrated field demonstration.

Recommendation 5

NASA should strengthen its program in sensor technology research and development, including piloted and unpiloted airborne sensor deployment for testing new sensors and as a platform for collecting and transmitting data useful for applications.

Recommendation 6

In addition to partnerships with other Federal agencies for the development and testing of experimental sensors that are of a particular interest to agencies, the Nation, and especially NASA, should explore additional strategic partnerships with space agencies in other countries and regions, such as the European Space Agency (ESA), Japan (JAXA), France (CNES) and Canada (CSA).

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Recommendation 7

NASA (and NOAA) should work with NSF and other agencies to assure that plans for incorporation of space-based and airborne observations (from both existing and, preferably, planned or proposed missions) are part and parcel of the experimental design of these proposed observatories.

Recommendation 8

Advanced cyberinfrastructure should not only be incorporated as part of planned observatories and related initiatives to help manage, understand, and use diverse data sets, but should be a central component in their planning and design.

Recommendation 9

Utilization of web-based services, such as collaboratories (i.e., web-based systems where researchers and users come together to build a system of data, predictive models, and management projects), for the distribution of observations, model predictions and related products to potential users, should be encouraged.

Recommendation 10

NASA and NSF should develop and strengthen program elements focused on demonstration projects and application of data assimilation in operational settings where researchers work collaboratively with operational agencies.

Recommendation 11

NASA should take the lead by expanding support for the application of integrated satellite remote sensing data products. NSF, NOAA, and other federal and state agencies engaged in environmental sensing should likewise expand support for the creation of the integrated digital products that meet educational, modeling, and decision support needs.

Recommendation 12

Congress, through the budgetary process, should develop a strategy for transitioning NASA experimental satellite sensors to operational systems so that the nation's investment in remote sensing can be utilized over the long term by other federal agencies and users by assuring data continuity.

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Recommendation 13

Water agencies should be alert for opportunities to incorporate new sensor and modeling technologies that will allow them to better deliver their mission and be more productive.

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Committee on Integrated Observations for Hydrologic and Related Sciences

Water Science and Technology Board

Division on Earth and Life Studies

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Preface

This report is a product of the Committee on Integrated Observations for Hydrologic and Related Sciences. The committee was organized under the auspices of the Water Science and Technology Board (WSTB) of the National Research Council and the WSTB's Committee on Hydrologic Science (COHS).

This study has interesting origins. The initial idea for the study arose from discussions at the COHS in 2003, and took the form of a one-page prospectus titled *Hydrology from Space*. While the prospectus mentioned integrating space-based observations with *in-situ* observations, as envisioned it emphasized a top-down approach. It would have assessed the usefulness of remotely sensed observations for flood and drought prediction and for snow pack measurement, and evaluated the scientific and technical readiness for observations of selected hydrologic states, among other tasks. An assurance of partial funding for the project was made at that time by the Terrestrial Hydrology Program of the National Aeronautics and Space Administration (NASA).

However, a near simultaneous effort was underway for a broader NRC "decadal survey" to help set an agenda for observations in support of *Earth Science and Applications from Space*. Among that committee's key tasks were to develop a consensus on the top-level scientific questions that should provide the focus for Earth and environmental observations for a 10-year period and to develop a prioritized list of recommended space programs, missions, and supporting activities to address those questions. Among the seven study panels organized under that study was a water panel, whose mission would have overlapped somewhat with this study as originally envisioned.

Around the same time, the COHS was made aware that the National Science Foundation (NSF) was considering the establishment of "observatories" with field measurements and cyberinfrastructure to assemble water data into a common framework. At the time, planned observatories included the HYDRO program of the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) in NSF's GEO directorate and the Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) supported by the Engineering Directorate (these two are now being combined into a program called WATER and Environmental Research Systems [WATERS] Network), along with the National Ecological

Observatory Network (NEON) supported by the Biological Sciences Directorate and the Critical Zone Observatories (CZO) funded by the Directorate for Geosciences. (As of this writing, not all of these proposed activities have been funded.) And the USGS, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Agriculture (USDA), and other agencies had been collecting various data from field measurements and experimental watersheds for many years and were exploring ways to use modern technology to increase information content and reduce costs.

Thus, while NASA, NOAA, and the U.S. Geological Survey's (USGS) Earth Resources Observation Systems (EROS) Data Center were collecting satellite information, other programs were collecting field data and additional data-intensive programs were planned for the near future. But how would the collection of these data and information be optimized? How would satellite, airborne, and in-situ data be integrated? What overarching principles might be followed? This was an issue of considerable interest to NSF and, as it turned out, to other federal agencies, including NASA.

The committee met six times between February 2005 and September 2006 in open and closed sessions. Representatives from many federal, state, and non-governmental agencies attended and participated in open sessions. This report is based on those discussions, the scientific literature, and the best professional judgment of the committee members.

The committee was deeply saddened by the September 30, 2005 passing of Leal Mertes, who was a respected and well-liked colleague and a valued committee member. We are grateful for her contributions both to this report and to our own lives.

We have many other people to thank for their help over the course of this project and in the preparation of this report. In particular, we would like to express appreciation to the following individuals for their presentations, discussions, and written submissions: Peter Arzberger, University of California-San Diego; Chaitan Baru, San Diego Supercomputer Center; Elizabeth Blood, National Science Foundation; Art Charo, NRC Space Studies Board; Tim Cohn, U.S. Geological Survey; Jared Entin, National Aeronautics and Space Administration; Frank Gehrke, California Cooperative Snow Surveys; Tom Harmon, University of California-Merced; Robert Hartman, National Weather Service; Jin Huang, National Oceanic and Atmospheric Administration; Doug James, National Science Foundation; Toshio Koike, The University of Tokyo; Richard Lawford, GEWEX; Dennis Lettenmaier, University of Washington; Kent Lindquist, Lindquist Consulting; David Maidment, University of Texas at Austin; Robert Mason, U.S. Geological Survey; Tom Nicholson, Nuclear Regulatory Commission; Peter van Oevelen, University Wageningen, The Netherlands; Jeff Talley, University of Notre Dame; and Stu Townsley, U.S. Army Corps of Engineers.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible and will ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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We wish to thank the following individuals for their review of this report: Jean Bahr, University of Wisconsin-Madison; Matthew Becker, University of Buffalo; Charles T. Driscoll, Syracuse University; Dara Entekhabi, Massachusetts Institute of Technology; Tony R. Fountain, University of California, San Diego; Charles D. D. Howard, Canada; Anne W. Nolin, Steven W. Running, University of Montana; Anne W. Nolin, Oregon State University; and Claire Welty, University of Maryland, Baltimore County;

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Mary P. Anderson, University of Wisconsin-Madison. Appointed by the National Research Council, Dr. Anderson was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Kenneth Potter, *Chair*
Eric Wood, *Vice Chair*

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