

# Integrating Multiscale Observations of U.S. Waters

Effective water management requires tracking the inflow, outflow, quantity and quality of ground-water and surface water, much like balancing a bank account. Currently, networks of ground-based instruments measure these in individual locations, while airborne and satellite sensors measure them over larger areas. Recent technological innovations offer unprecedented possibilities to integrate space, air, and land observations to advance water science and guide management decisions. But to realize these possibilities, agencies, universities, and the private sector must develop new sensors, test them in field studies, and help users to apply this information to real problems.

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.

Effective management of water resources will require improvements in our capacity to understand and quantify the water cycle and its interactions with the natural and built environment. Natural ecosystems are adapted to patterns of stream discharge, precipitation, and evaporation, and to the amounts of nutrients such as nitrogen and phosphorous that are in the water. Adjustments in the water cycle due 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 good news is that recent and potential future technological innovations offer unprecedented possibilities to observe, understand, and manage hydrologic systems. Sensors, which are used to take various measurements, are becoming smaller, less expensive, and are requiring less power, allowing for deployment in much larger numbers. Researchers are designing sensors to provide previously unavailable information, such as real-



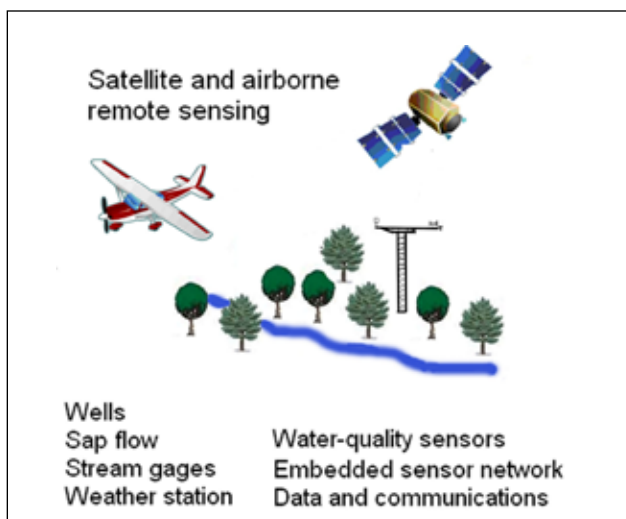
## Ins and Outs of Water Flow

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.

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. However, there are gaps between the vision of what researchers and managers want to achieve and their ability to realize that vision.

This report examines the potential for integrating new and existing satellite, airborne, and ground-based observations to gain holistic understanding of hydrologic and related chemical

and ecological processes in support of water and related land-resource management. How can the cooperation needed to achieve this integration be facilitated? And how can integrated hydrologic measurements provide greater benefit to local or regional decision-making?



### ***THE CHALLENGE OF UNDERSTANDING WATER FLOWS AND STORES***

There are two main challenges to understanding and quantifying the movement of water between and within surface water, groundwater, soil water, and the atmosphere, 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 change from place to place and from time to 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, remote sensing methods are used to provide information on the spatial distribution of hydrologic 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 of water resources 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 or limited access.

The report identifies the following as the most important challenges to be overcome:

**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. All of the required technologies are expensive to develop, and most will at least initially require public funding until their commercial viability is established. Thus, 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 local 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 many kinds of 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) a 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.

## RECOMMENDATIONS

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

**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 case studies discussed in the report. 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 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.

**Developing 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.

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**This report brief was prepared by the National Research Council based on the committee's report.** For more information or copies, contact the Water Science and Technology Board at (202) 334-3422 or visit <http://nationalacademies.org/wstb>. Copies of *Integrating Multiscale Observations of U.S. Waters* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; [www.nap.edu](http://www.nap.edu).



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