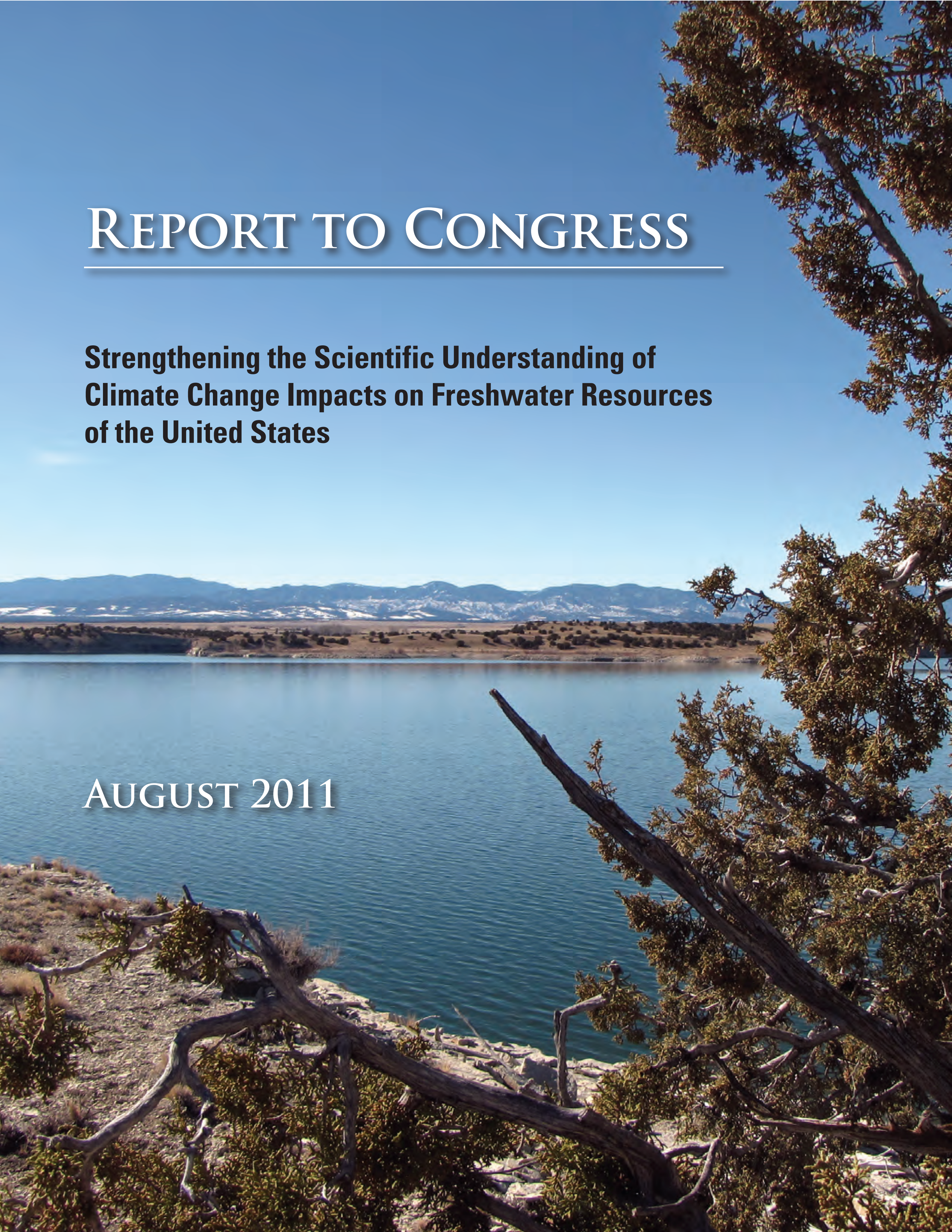
Report to Congress

Strengthening the Scientific Understanding of Climate Change Impacts on Freshwater Resources of the United States

August 2011



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Cover. Pueblo Reservoir in south-central Colorado. Photograph by Robert Stogner.

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Executive Summary

This report responds to the requirements of Section 9506 of the Omnibus Public Lands Act [Public Law (PL) 111–11; Appendix A] calling for a report to Congress that describes the impacts of global climate change on freshwater resources of the United States, and identifies key actions to improve the Nation's capacity to detect and predict changes in freshwater resources that are likely to result from a changing climate. The steps described in the report are intended to help decision-makers and water resource managers by facilitating improvements in observational data, data acquisition, and modeling capabilities.

Freshwater resources are vulnerable to a number of stressors, and a changing climate can exacerbate other stressors and creates new risks to the Nation's food security, energy security, and overall economic health. Some key impacts of climate change on water resources that have been identified to-date (U.S. Global Change Research Program, 2011) include:

- Increasing air and water temperatures;
- Declining rainfall amounts in some areas and increasing amounts in other areas, and decreasing proportion of precipitation that falls as snow;
- Changes in the timing of snowmelt runoff;
- Decline in the mass of water stored in glaciers;
- More intense rainfall and storm events;
- Rising sea levels; and
- Changing quality of freshwater, coastal, and ocean waters.

The Nation invests considerable resources in monitoring, mapping, evaluating, assessing, modeling, and managing water resources. Many of the existing observational water data networks, models, and hydro-statistical methods were developed for specific users and pre-date recent advances in climate change science. As a result, these systems (networks, methods, and models) were not designed to consider climate-induced stressors, to account for non-stationary hydroclimatic processes, or to evaluate the effectiveness of climate change mitigation and adaptation strategies. Today, there is a need and an opportunity to modernize hydroclimatic data networks and climate-relevant data collection, data management, mapping, modeling, and information dissemination. Of particular importance is maintenance and strengthening of long-term *in situ* and remote observational capabilities to detect change.

This report provides a general overview of the challenges that a changing climate poses for water resource managers in the context of other water-resources stressors. In particular, the report considers water resources measurement and modeling systems that are relevant to climate change adaptation, as required by Section 9506. Recommendations are focused on Federal actions to strengthen these systems to inform water management decisions at the Federal, State, and local levels. This report draws from and builds on a number of recent climate and water documents that have been produced across the Federal, State, local, Tribal, and private water sectors.

Observational data, the networks that provide these data, the systems that make these data available, and the models that enable projections of future climate conditions are critical for decision-making. Hydrologic data, science, and technology need to be coordinated and improved to promote the ready interoperability of data and models, and ultimately provide decision-makers with more effective information, tools, and services.

Findings

The key findings for each of the six "review elements" included in the statute (that is, Section 9506 of PL 111-11) are summarized below; findings for review elements 1 and 2 are combined.

Review Elements 1 and 2. Assess adequacy of current hydroclimatological observation networks and identify gaps in current networks.

Finding 1: Broad Support for Improved Monitoring Systems. There is broad and continuing support from a wide constituency to sustain and strengthen the Nation's hydroclimatic monitoring systems, including research to support those systems. In particular, adaptive management and water-resources planning tools are only effective when supported by strong data networks.

Finding 2: Streamflow Data. The National Streamflow Information Program was begun in 2003 with 5 program goals. These goals are to (1) develop a stable stream-gaging network; (2) conduct intensive data collection during floods and droughts; (3) conduct regional and national streamflow assessments; (4) improve data delivery; and (5) invest in methods development research. Current progress toward meeting the goals include 15 percent of the stable stream-gaging network in place with some improvements in data delivery.

Finding 3: Streamflow Information Coordination. Streamflow information is collected by a variety of Federal and State agencies, generally for agency-specific purposes. Tremendous benefits could be gained for the Nation if these disparate data sets were more broadly available, interoperable, and included information on methods of collection, quality, and accuracy.

Finding 4: Reservoir and Lake Data. Reservoir water-level and volume information is collected by a variety of Federal agencies and private entities. Data are not widely available, and reservoir volume information generally is out of date. No data are available for many natural lakes, and a national lake level network does not exist.

Finding 5: Groundwater-Level Monitoring. The Advisory Committee on Water Information's Subcommittee on Groundwater has developed a comprehensive national groundwater monitoring network that could provide data and information necessary for planning, management, and development of the Nation's groundwater resources in a sustainable manner. This network was authorized in Section 9507 of PL 111-11.

Finding 6: Soil Moisture. Numerous specialized soil moisture networks exist across the Nation, but there is no design for a national soil moisture network. The NASA Soil Moisture Active Passive Mission, planned for 2014, in conjunction with a robust *in situ* network for calibration, could provide adequate soil moisture data for many applications at regular intervals over much of the country if these efforts were implemented in a coordinated manner.

Finding 7: Evapotranspiration. Operational evapotranspiration data can be obtained from remotely-sensed information. *In situ* measurements of energy, carbon, and water fluxes above the canopy provide valuable information on water budgets (as well as energy and carbon budgets) and are valuable for improving remotely-sensed evapotranspiration estimates, but the number of such installations is relatively small.

Finding 8: Precipitation Frequency-Duration-Intensity Estimates. A systematic and consistent approach that includes recent data and improved statistical techniques is needed for updating precipitation intensity-duration-frequency estimates.

Finding 9: *In Situ* Precipitation Measurement. There is an opportunity to form a robust precipitation measurement network in the U.S. with existing gages operated by numerous Federal, State, and local agencies, research organizations, and private citizens. However, lack of coordination, protocol, and communication among the organizations impedes formation of such a network. Because of this lack of coordination among precipitation gage operators, there has been no broad analysis of precipitation measurement needs.

Finding 10: Remotely-Sensed Precipitation Measurements. Radar and satellite precipitation measurement capabilities have provided precipitation estimates over areas not covered by ground-based gages. These estimates, however, rely on gage data for calibration and bias correction.

Finding 11: Snowpack Monitoring. The Natural Resources Conservation Service's SNOTEL (SNOwpack TELemetry) network operates in 12 western States and Alaska. NRCS has proposed to coordinate and provide technical leadership for collection and dissemination of snow information over a greater area of the U.S., which could enhance products from NOAA's Snow Data Assimilation System.

Finding 12: Glacier Monitoring. Glacier monitoring is important, given the potentially large effect glacier meltwater could have on sea level and ocean circulation. A combination of ground-based and satellite monitoring is warranted. As in many monitoring efforts, there is some lack of coordination among existing monitoring activities.

Finding 13: Water-Quality Networks. Extensive water-quality monitoring is conducted in the U.S., and various networks have evolved to meet user needs. Integration of data from the various networks could offer benefits, if data were comparable and well integrated. The proposed National Monitoring Network offers a sound basis for understanding fluxes of key contaminants from major basins across the Nation.

Finding 14: Waterborne Pathogens. Prevalence of waterborne pathogens, including harmful algal blooms, likely will change in response to rising temperatures, as well as to alterations in flow characteristics and contaminant loadings. Systems for tracking these changes are not well developed, nor are they well integrated with geospatial, water-quality, and public health information.

Finding 15: Wetlands. Freshwater and coastal wetlands are sensitive to changes in hydrologic and sea-level conditions. The National Wetland Assessment should provide valuable information on the conditions of a sampling of the Nation's wetlands, and a basis for future comparisons, although information on specific systems will not be available. Implementation of the new wetlands mapping standard needs to be expedited.

Finding 16: Withdrawals and Consumptive Use of Water. Water withdrawal and consumptive use data, particularly as related to the Nation's energy portfolio, are inadequate for making long-term decisions about water availability in the U.S.

Finding 17: Environmental Flows. New data and research on the environmental flow requirements, including pre- and post- alteration information, are needed for the restoration and maintenance of healthy aquatic ecosystems.

Review Element 3. Improve data management to increase utility of the information that is collected and efficiency of data acquisition and reporting.

Finding 18: Interoperable Data Systems. Ready access to the full range of hydroclimatic data collected by government agencies and other interests is inadequate. Data are collected using a range of protocols, which are not always documented, and are archived in a variety of ways, from modern relational databases to paper copies in files. There is much to be gained from use of consistent documentation standards and improvements in interoperability of data systems.

Finding 19: Data and Decision-Making. In general, hydroclimatic data are insufficiently integrated (or readily integratable by the user community) to support important management decisions, and hydroclimatic data are inadequately connected to information on issues of social relevance.

Review Element 4. Establish a data portal to enhance access to water resource data across agencies.

Finding 20: New Data Portals. A new effort by the U.S. Global Change Research Program, using existing agency resources, has been initiated to build an interagency data portal, and this portal also may provide access to hydroclimatic data. The initial phase of this process, conducted with strong coordination among Federal and non-Federal partners, is expected to focus on data generated in support of the National Climate Assessment. The portal also is expected to provide guidance on appropriate use of data and on the use of probabilistic information. Other efforts to better organize data, such as the Integrated Water Resources Sciences and Services activity, also should contribute to enhanced data access.

Review Element 5. Facilitate the development of hydrologic and other models to integrate data that reflects groundwater and surface water interactions.

Finding 21: Hydroclimatic Statistics and a Changing Climate. Statistical models of hydroclimatic events that are based on the assumption that future conditions will have the same statistical properties as past conditions are not valid. Improved understanding of the statistical characteristics of precipitation and streamflow are needed for effective planning and management under uncertainty.

Finding 22: Integrated Modeling. Although there have been recent advances, current coupled groundwater-surface water models, and fully coupled hydrologic-water quality-ecosystem models are inadequate for forecasting the full range of effects of management actions and/or climate change on the entire resource.

Finding 23: Global Climate Models. There is a need to develop and rigorously test downscaled Global Climate Models (GCM's) to provide more reliable projections of conditions for for water-resources planning applications, and develop guidance for appropriate applications.

Review Element 6. Apply hydrologic information to resolve water resource problems including improvement of ecological resiliency.

Finding 24: Existing Coordination. Significant ecological and social benefits are expected from enhanced coordination of water-related data collection and integration of activities across the Federal government and with non-Federal partners.

Finding 25: Existing Coordination Mechanisms. Federal agency actions towards improving data integration should continue and be accelerated through the Subcommittee on Water Availability (SWAQ) and the Advisory Committee on Water Information (ACWI). SWAQ should be strengthened to better promote cross-agency communication and additional coordination opportunities. The Advisory Committee on Water Information provides a useful, and perhaps under-utilized forum for collaboration on the collection, storage, management, analysis, and dissemination of climate-relevant water information between Federal and Tribal, state, and local agencies.

Next Steps

Effective management of the Nation's water resources will require meaningful action to address many of the shortcomings that were identified in this report on hydroclimatic observational and modeling systems. Moreover, continued vigilance and effort will be required to sustain and enhance vital observation and modeling systems that currently are in place and operating effectively over a period of years. Federal agencies should consider amending existing programs and policies to incorporate these actions whenever possible and should consider these actions in future budget planning.

This report does not prioritize among the needs that were identified, but prioritization will be required as Congress and the water-resources community begin to deliberate on these findings. Certainly, high priority should be given to maintaining existing capabilities, as measurements of hydroclimatic processes that are not made can never be recovered, creating unrecoverable gaps in the systematic record. Findings in this report that are supported by other documents (for example, the National Monitoring Network and the National Groundwater Monitoring Network) and those groups also deserve priority consideration.

Key next steps for Federal agencies to implement the findings of this report are described below.

1. Strengthen observational data systems for fresh-water resources and climate change.

- Strengthen existing efforts, including the Water Census, through enhancements to the hydroclimatic observational network identified in **Review Element 1** of this report. Information that is critical from a health, safety, and welfare perspective should be given priority, while considering the data needs of land, water and environmental resource managers. Effects on water resources from energy extraction and production, and carbon sequestration (both geologic and biological) need increased emphasis.

- Conduct ongoing and sustained analyses of hydroclimatic data to identify emerging trends and patterns and to develop new insight into hydroclimatic variability.

2. Prioritize observational systems that fill important gaps in understanding water supply reliability.

- Enhance collection of water-use information, including provision of timely information on withdrawals and return flows (quantity and quality) from surface and groundwater resources and information on withdrawals and consumptive use by sector.

- Implement the proposed National Streamflow Information Program and the National Groundwater Monitoring Network, both of which are authorized in PL 111-11.

- Develop and implement a national lake/reservoir level and contents data network.

- In partnership with private industry, conduct research on new monitoring technologies, including sensors, data transmission, automated quality assurance, and remote-sensing technologies.

3. Improve water-quality and ecosystem monitoring systems.

- Implement the National Water-quality Monitoring Network, which is supported by the Advisory Committee on Water Information and is consistent with the National Ocean Council's Strategic Action Plans.

- Enhance interagency efforts and support States to monitor and improve mapping of wetland areas and habitat quality on a seasonal basis.

- Implement a waterborne disease tracking network, including all appropriate ancillary data.

4. **Strengthen links between hydroclimatic observational data systems and climate models; improve data management, acquisition, analysis, and reporting.**

    - Link monitoring, observational systems, climate model outputs and other data systems, to update and improve hydroclimatic statistics that support high-priority water management decisions (particularly related to water supply reliability and quality).

    - Build on the initial foundation established by the Integrated Water Resources Science and Services activity to expand and encourage the use of consistent data standards across agencies and with non-governmental partners and other ways to integrate existing data into more comprehensive water information systems.

    - Develop new and improved models (both statistical and deterministic) for assessing hydroclimatic data, developing design conditions, and forecasting likely future conditions for expected scenarios.

    - Develop guidance for water managers on appropriate use of probabilistic projections and model outputs.

5. **Support the establishment of an interagency climate data portal and provide access to high priority water-related datasets.**

    - Promote interagency coordination of diverse data and define the architecture of data systems for freshwater resources to facilitate improved access to these data through a single portal. As a part of the portal, provide for user feedback, including recommendations for improvements or modifications.

6. **Strengthen coordination to improve the quality and accessibility of freshwater data systems including technical outreach and support to stakeholders and decision-makers.**

    - Request that the Subcommittee on Water Availability and Quality (SWAQ) monitor progress on implementing the findings and recommendations of this report and provide annual updates to the National Science and Technology Council and member agencies, and to non-Federal partners.

    - Promote interagency coordination and cooperation to implement the National Water Census (*http://water.usgs.gov/wsi/)* and Integrated Water Resources Science and Services (National Oceanic and Atmospheric Administration, 2011k).

    - Encourage the Advisory Committee on Water Information, an existing Federal Advisory Committee, to establish a new subcommittee or other appropriate mechanism, to solicit and consider input from the public and stakeholders on matters related to freshwater resources and a changing climate and relay these views to Federal water data program managers and the SWAQ.

    - Fully engage States, Tribes, local agencies, and interstate organizations, most of whom have water-resources management responsibilities, in the implementation of the findings in this report.

Introduction

> "We don't yet have the observation networks and capacities that we ought to have to keep track of what's happening on and to the Earth. . . . That priority on maintaining and expanding the data sets, the observations, the monitoring, is absolutely key. If you don't do that, you can never make up for it, in the sense that we will never know what the Earth was doing in places and times when we weren't monitoring it."
>
> *John Holdren, Science Advisor to the President* (Eos, 91(51):503-504)

Freshwater, one of the Nation's most valuable natural resources, is under increasing stress from changes in climate, changes in land use and land management, and growing demands for a variety of services. Water supplies and their supporting infrastructure are critical to the health and well-being of society and central to a vibrant economy, food production, energy reliability, and national security. The quantity and quality of freshwater affects the viability of riparian ecosystems, aquatic habitats, and wetlands that support fisheries, wildlife, and recreational activities.

The effects of a changing climate greatly complicates day-to-day management of freshwater and long-term planning for infrastructure to support the Nation's freshwater needs. Documenting, understanding, and predicting the effects of climate change on freshwater supplies and quality remains a significant challenge for the Nation's water-management and scientific community. The consequences of human activities and a changing climate on freshwater already being observed include:

- Changing precipitation patterns (frequency, storm intensity, timing, etc.) that lead to flooding or drought conditions, pollutant runoff from land surfaces into freshwater resources, and disruption of aquatic habitats (for example, Christensen and others, 2007, Intergovernmental Panel on Climate Change, 2007a and 2008);

- Altered snowpack characteristics (depth, density, storage capacity or water equivalent, temperature, melt rate, etc.), that affect timing and volume of snowmelt runoff and the capacity of reservoirs to store water (for example, McCabe and Wolock, 2002);

- Changing sea levels that affect coastal and near-coastal environments, increase impacts of coastal storms on nearshore populations and infrastructure, increase saltwater intrusion into groundwater resources, disrupt water-resources infrastructure, and impair the health of coastal wetlands (for example, Karl and others, 2009); and

- Disruption of healthy aquatic ecosystems due to changing patterns of air and water temperature, precipitation, water quality, land use, and water allocation (for example, Christensen and others, 2007; Intergovernmental Panel on Climate Change, 2007a and 2008; Karl and others, 2009).

A number of agencies and research groups, including the United States Global Change Research Program (USGCRP), are actively engaged in evaluating the effects of climate change on human and natural systems in the United States, including freshwater resources. The recent USGCRP national assessment, released in 2009 (Karl and others, 2009), highlights the importance of providing decision-makers with appropriate data, tools, and models for climate change adaptation. In addition, in its 2010 Progress Report (Council on Environmental Quality, 2010), the Interagency Climate Change Adaptation Task Force (Task Force) called for "improving water resource management in a changing climate." The Task Force, established in 2009 to provide overall direction and guidance to Federal agencies in matters relating to adaptation to climate change, has identified three key actions related to water resource management, one of which is to "strengthen data and information systems for understanding climate change impacts on water."

Congress recognized the importance of supporting water resources decisions when it enacted Section 9506 of the Omnibus Public Lands Act (Public Law 111–11) in March of 2009 (Appendix A). Section 9506 calls for a report to Congress describing the current scientific understanding of impacts of global climate change on the freshwater resources of the United States.

This report was developed in response to the requirements of Section 9506 by an interagency team of water scientists and program managers (Appendix D). The Interagency team cooperated with the Subcommittee on Water Availability and Quality (SWAQ), an interagency subcommittee of the National Science and Technology Council (NSTC), Committee on Environment Natural Resources, and Sustainability (CENRS) (*http://www.whitehouse.gov/administration/eop/ostp/nstc/committees/cenrs*) and the Interagency Climate Change Adaptation Task Force (*http://www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation*), and its Water Resources and Climate Change Adaptation Workgroup. The interagency team also collaborated with a broad range of interested parties including those represented on the Advisory Committee on Water Information (ACWI) (*http://acwi.gov/sogw/pubs/tr/index.html*).

Climate-Relevant Water Resource Challenges

Every day, all across the Nation, decisions are made that affect the quantity, quality, and sustainability of water resources. These decisions can have significant economic, health, social, and environmental implications. Some decisions directly affect local water availability such as surface- and groundwater withdrawals and infrastructure development to support drinking water systems, irrigation, energy production, or industrial activities. Decisions regarding land management and development, energy development and fuel extraction, degree of wastewater treatment, and reservoir release schedules also affect water resources. Decision-makers need ready access to reliable data, effective data management, and up-to-date analyses and scientific tools in order to ensure a safe and reliable water supply for humans and ecosystems, today and into the future.

Decisions regarding mitigation of, or adaptation to, effects of climate change also can directly affect water resources. For example, shifts in our national energy portfolio such as increased use of alternative energy sources (for example, biofuels, solar, wind), increased energy efficiencies, or alternative approaches for resource extraction (for example, the use of hydraulic fracturing) can affect local or regional water availability and quality (Electric Power Research Institute, 2002; Mielke and others, 2010). Similarly, the use of carbon capture and sequestration to control greenhouse gas emissions can impact aquifers and surface waters (Dooley and others, 2006; Intergovernmental Panel on Climate Change, 2005). It is, therefore, important to maintain or develop adequate data collection systems that focus on the water related implications of a wide range of decisions and understand the net effect on future water availability and quality (U.S. Environmental Protection Agency, 2010b).

High priority water resources challenges that are affected by climate can be categorized into four interrelated areas:

- Assuring an adequate water supply;
- Protecting human life, health, and property;
- Protecting the quality of freshwater resources and the ecosystems they support; and
- Protecting coastal and ocean resources and the ecosystems they support.

Climate-relevant aspects of each of these challenges are highlighted below. Water managers and decision-makers need access to robust and reliable data, modeling capabilities, and information exchange systems to predict, respond, and adapt to a changing climate.

Assuring an Adequate Water Supply

Federal, State, and local governments, utilities, farmers, energy companies, industry, and private citizens all make decisions that affect and are impacted by the availability, reliability, and quality of water supplies. Critical freshwater needs include:

- Drinking water supplies;
- Agriculture and food security;
- Energy development, production, and generation;
- Industrial cooling and process water;
- Navigation;
- Recreation, and tourism; and
- Healthy aquatic ecosystems.

Water managers and decision-makers need to ensure that water is safely managed and that enough water of the appropriate quantity and quality is available at the necessary time and place to support ecosystems as well as human needs. In addition to climate change, improvements in water-use efficiency, advances in technologies (for example, irrigation, energy, and industry), changes in land-use and development patterns, and changes in the economics of delivering water to end-users need to be considered in water supply decisions.

To assure an adequate water supply now and into the future, water managers and decision-makers need the capacity to understand and anticipate:

- The manner in which aquatic ecosystems respond to the short- and long-term changes in freshwater quantity, quality, and availability;
- Historical patterns and projected trends in annual and seasonal variability in streamflows, groundwater levels, and snowpack characteristics to improve water use planning and provisioning;
- The effect of climate, water management decisions, and land-use on water required for agriculture and energy, water and wastewater treatment requirements, human health risks, and aquatic ecosystem health;
- Changes in water quality in response to the types and quantities of chemical and microbial contaminants, warmer and more variable water temperatures, different flow patterns, and alternative water resource management practices (stormwater and rainwater collection and reuse, water-use efficiency, and hybrid systems for centralized and decentralized water reclamation and reuse); and

- Impacts of climate, land-use, and water management practices in conjunction with streamflows, precipitation patterns, and groundwater recharge on saltwater intrusion into freshwater aquifers and estuaries and salinity in water supplies.

Robust and continued measurements are needed to determine the extent to which changes are occurring, the rate of change in both trends and extremes, and the likelihood of crossing thresholds of significance in ecological and hydrologic systems. The continued, and in some cases, enhanced, collection and documentation of data in a systematic, reliable, and defensible way is critical. As climate, land use, economic, and sociological factors change, data and derivative products form the basis of predictive tools and models to estimate and evaluate factors that affect the amount and quality of water resources likely to be available in the future. Integrated data networks, mapping, and modeling tools provide a basis for predicting potential impacts of climate change at local, regional, and national scales. Equally important are effective protocols and policies for sharing and continually updating the data and tools. Examples of the information needs that underpin water resource decisions are given in table 1.

Table 1. Examples of water resource decisions related to climate.

Example of type of decision	Information requirements
Allocating water resources for specific end-uses: • Upgrade existing water systems and develop new supplies to support communities, industry, energy, and agriculture. • Design and operate irrigated and rain-fed agricultural facilities; decide which crops to plant and the extent to which irrigation is needed. • Ensure water availability for reliable power production (hydroelectric, thermoelectric, solar), resource extraction, and other industrial uses (manufacturing, food processing, electronics, biotechnology, etc.). • Ensure sufficient water levels to maintain navigation efficiency and safety. • Ensure adequate water of sufficient quality for endangered species. **Water and related infrastructure:** • Protect the security of our Nation's water infrastructure. • Protect human safety, transportation, and other infrastructure from potential increases in flooding. • Design and operate water storage for agricultural, municipal, and industrial purposes. • Design, operate, upgrade, or rehabilitate degraded water infrastructure (dams, reservoirs, canals, navigational systems, pipelines, storage facilities, drinking water supplies, wastewater and stormwater management, and reuse systems, etc.). • Size and site facilities to manage, process, and convey drinking water, wastewater, return flows, and stormwater. • Design and operate groundwater recharge systems to maximize short- and long-term storage capacity..	**Water availability:** • Statistical estimates of precipitation frequency, intensity, and duration. • Flood and drought frequency, magnitude, and duration. • Streamflow statistics. • Groundwater storage capacities, recharge rates, and rates of change of groundwater supplies. • Snowpack characteristics. • Glacier characteristics (area, volume, rate-of-change, etc.). • Water-quality conditions. • Sea-level rise patterns and trends. **Water allocation and use patterns:** • Estimates of amount and timing of water withdrawals, demand, and return flows by communities, municipalities, agriculture, industry, and energy production systems. • Uptake and water use requirements for crop production to optimize irrigation scheduling. • Requirements for quantity and quality of environmental flows and levels to support ecosystem structure and function. • Water rights, interstate agreements, compacts, and court decrees. • Congressionally authorized reservoir regulation requirements. • Groundwater withdrawal rates. • Cooling water, water use, and wastewater generation rates for thermoelectric power plants and industry (incorporating water footprint of greenhouse gas mitigation strategies and advances in water-use efficiency), as power demands for cooling increase.

Protecting Human Life, Health, and Property

Decisions that are made on a daily basis by Federal, State, and local governments, property owners, and insurance industries collectively influence the means by which human life, health, and property are protected from water-related hazards and the means by which the effects of these hazards are mitigated. Key challenges that are relevant to climate change include potential risks associated with:

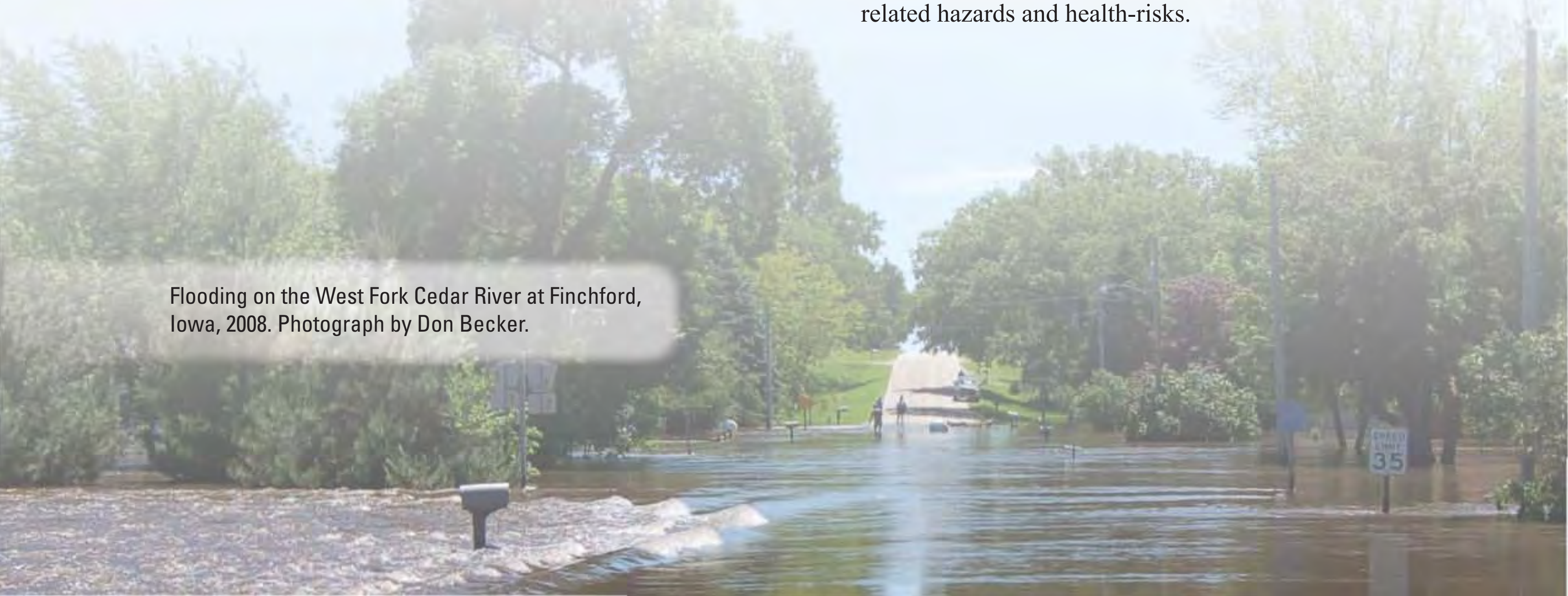
- Increased potential for loss of life due to changes in the frequency and intensity of precipitation and related flooding;
- Increased incidence of waterborne and vector-borne disease because of changes in water characteristics that affect survival and proliferation of pathogens and vectors;
- Increased cost and energy requirements for producing safe drinking water due to changes in water quality and increased salinity;
- Increased cost and energy requirements for water withdrawals due to lowered groundwater levels and changes in surface water levels;
- Increased potential for drought in some areas leading to altered water quality or quantity;
- Disruptions of power, water, sewer, and emergency services, and failure of flood control and water storage structures, as a result of more extreme rainfall, storm events, and sea-level rise;
- More intensive wildfires in some areas, which affect the quantity and quality of water; and
- Reduced "ecosystem services" within watersheds (ability of the natural system to support outcomes that are economically valued, such as flood control, erosion control, and improvements in water quality that come from filtering by natural systems).

High priority issues for water managers and decision-makers that have been identified in a variety of forums and publications include (for example, Johnson Foundation, 2010):

- Connecting land use and water supply decisions in the context of changing climatic conditions, including implications for ecological impacts;
- Developing early warning systems to prevent and respond to waterborne disease outbreaks;
- Preventing major disruptions to energy supply and water and sewage services (for example, large water main breaks requiring community-wide boil water advisories);
- Identifying areas prone to water inundation to develop appropriate warning, response, and control systems, particularly in urban and developing areas;
- Protecting human safety and economic development through flood mitigation; and
- Assuring adequacy of cooling water for thermoelectric/nuclear power plants.

The types of monitoring and modeling systems needed to protect human life, health, and property are similar to the information needs highlighted in table 1. However, specific attention may be required for documenting incidence of waterborne disease and the proliferation of invasive species in a changing climate. Additional modeling and predictive tools are needed to:

- Predict relations between climate, human activities, and the occurrence and prevalence of waterborne disease vectors and other contaminants in water supplies;
- Forecast changes in water temperature and associated impacts on habitat;
- Understand health risks due to invasive species and microbial pathogens that can survive under changing climate conditions; and
- Identify and safeguard human and ecological populations that are vulnerable to water-related hazards and health-risks.



Flooding on the West Fork Cedar River at Finchford, Iowa, 2008. Photograph by Don Becker.

Protecting the Quality of Freshwater Resources

While considerable progress has been made in reducing pollution within watersheds, the number of impaired water bodies continues to increase (U.S. Environmental Protection Agency, 2011a). Governmental agencies (Federal, State, interstate, Tribal, county, and municipal) and private entities (universities, watershed associations, environmental groups, permitted dischargers, and local citizens) are actively engaged in tracking the occurrence, quantity, quality, distribution, and movement of surface and underground waters (U.S. Environmental Protection Agency, 2009). Significant efforts are being coordinated among the U.S. Environmental Protection Agency (USEPA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the U.S. Fish and Wildlife Service (USFWS), U.S. Forest Service, coastal States, and the National Estuary Programs (NEP) to evaluate ecological and water-quality conditions. For example, The National Water-Quality Assessment Program (NAWQA) (U.S. Geological Survey, 2011a) integrates monitoring data with geographic information on hydrological characteristics, land use, and other landscape features. Examples of other efforts include The National Water Information System (NWIS) (U.S. Geological Survey, 2011b) and the Wadeable Streams Assessment (WSA) (U.S. Environmental Protection Agency, 2006).

Protecting the quantity and quality of freshwater resources and aquatic ecosystems will become increasingly challenging due to the changing patterns of precipitation (intensity, frequency, and type), land use and land-cover change, increasing demands for water, and changing water management practices. Increasing air temperatures will pose direct challenges, including potentially higher evapotranspiration rates, likely leading to increased demand for water for irrigation and energy production. Regulatory agencies, local, State and regional governments, utilities, non-governmental organizations, and industries make decisions that can affect freshwater quality in various ways by:

- Altering local hydrodynamics (through infrastructure projects, water withdrawals, return flows, runoff, or discharges), resulting in changes in runoff patterns, contaminant levels, in-stream flows, and lake and groundwater levels;
- Implementing policy tools [for example, National Pollutant Discharge Elimination System (NPDES) wastewater and stormwater permits, Effluent Limitation Guidelines (ELGs), Water Quality Criteria and Standards (WQS), Designated Uses, and Total Maximum Daily Loads (TMDLs)] for managing impaired waters in accordance with the Clean Water Act;
- Developing and implementing Best Management Practices (BMPs) for managing agricultural and natural resources;
- Restoring and maintaining riparian buffers and floodplain bottomland hardwood forests to mitigate downstream flooding and sediment pollution during storm/flood events;
- Balancing competing water resource needs, including Congressionally authorized reservoir releases, flood risk reduction, and protecting downstream water quality (temperatures and other physical, chemical, or biological water-quality parameters);
- Changing and more variable temperatures, microbial ecology, biogeochemistry, or salinity (due to increased evaporation, discharges of salt-laden constituents, or release of nutrients or other contaminants associated with water use for domestic, industrial, or agricultural purposes);
- Managing water quality changes associated with energy systems (thermoelectric and nuclear power plant cooling), the development of alternative fuel sources (biofuels, shale-gas, tar sands, hydrogen, coal-bed methane), and carbon capture and sequestration;
- Managing and protecting aquifers that are being depleted by groundwater pumping and where aquifers are threatened by coastal subsidence sea level rise, and saltwater intrusion;
- Managing contaminant plumes that are mobilized in groundwater supplies due to increased pumping;
- Preparing for coastal inundation in places where the natural vegetative buffers are ineffective or no longer exist; and
- Addressing sediment loading into reservoirs and developing mitigation and prevention measures to control runoff from intense storms, landscape scale fires, and reservoir operations.

In many cases, water-quality issues are expected to be exacerbated by the impacts of a changing climate on the amount and timing of flows (for example, Larsen, 2010). These changes affect the delivery of contaminants and associated impacts on vulnerable aquatic ecosystems. For example, a large percentage of the total annual loads of nitrogen and phosphorus delivered to coastal ecosystems occurs during a few high-flow events, whereas the toxicity of many compounds is higher during the lowest flows. The extent to which waterborne contaminants (arsenic, fluoride, radionuclides, organics, gases, and microorganisms) are mobilized from aquifer material can vary in response to changes in groundwater levels related to natural and engineered recharge and withdrawal patterns. New health risks may be associated with localized microbial and ecological responses to higher temperature, and in conjunction with changes in contaminant delivery, will impact the population dynamics and survival of invasive species, pathogens, and algae.

Changes in the natural flow regime are an important contributor to degraded river ecosystems and loss of native species (Carlisle and others, 2010; Poff and Zimmerman, 2010). In a national study at 1,059 reference (unimpacted) and 2,888 other sites, (fig. 1) Carlisle and others (2010) compared maximum and minimum flows at the reference sites to those that would be expected to occur at the other sites. The extent of streamflow alteration from expected conditions was the primary predictor of biological integrity at all sites.

Measuring streamflow on the Cedar River near Cedar Rapids, Iowa. Photograph by Don Becker.

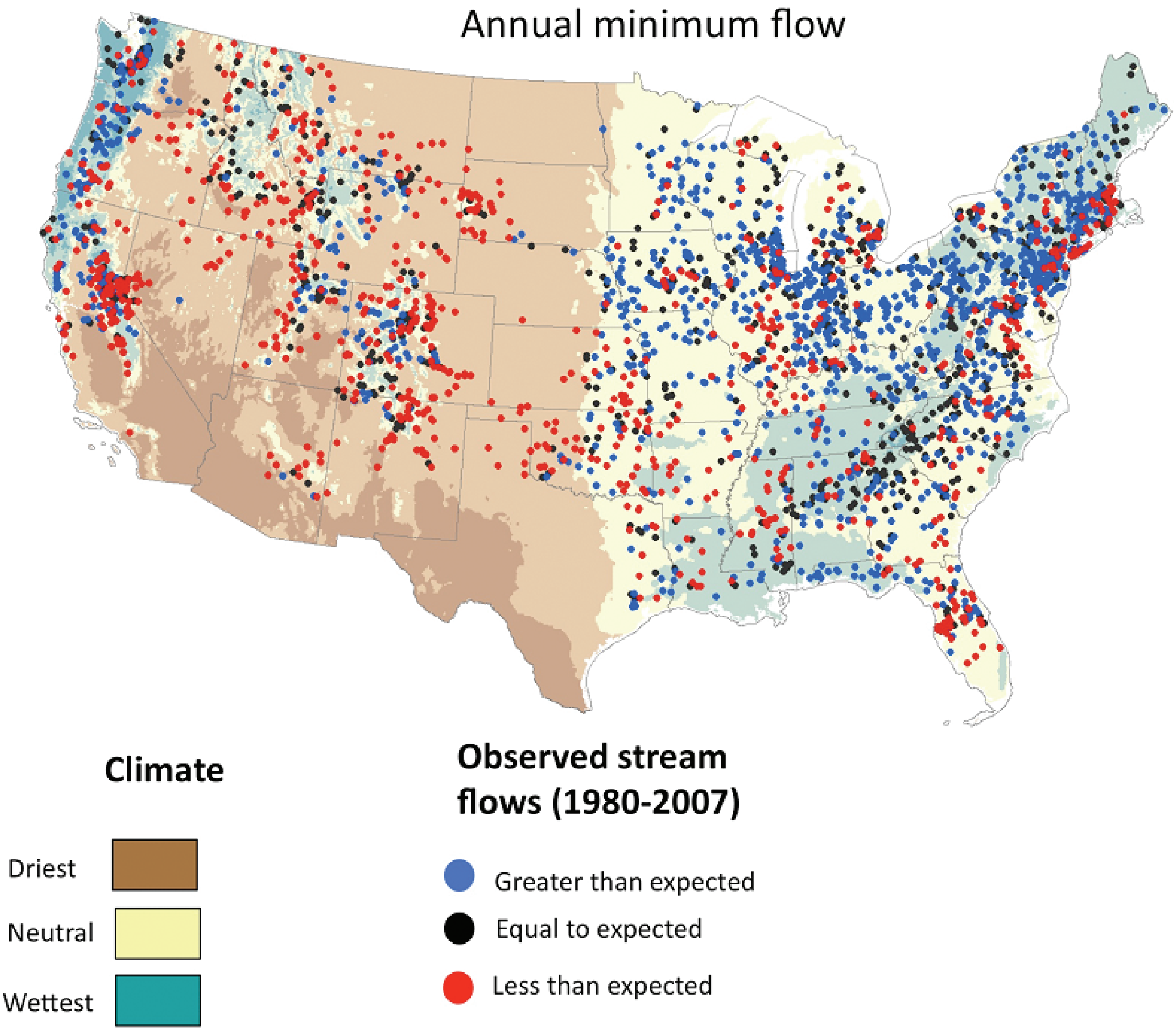


Figure 1. Alteration of minimum streamflow from expected minimum streamflow at 2,888 sites (Carlisle and others, 2010).

Protecting Coastal and Ocean Resources

Some of the most densely populated areas in the Nation are in the coastal regions. These regions play an integral role in the economy, supporting community well-being, commerce (ports), transportation, energy (oil, natural gas, refineries, wind, tidal and wave energy, solar), fisheries, tourism, and recreation. Coastal waters are valued for their ecological richness and encompass many unique habitats (estuaries, coastal wetlands, seagrass meadows, coral reefs, mangrove and kelp forests, and upwelling areas). Coastal ecosystems yield highly productive fisheries and provide breeding habitat for 85 percent of U.S. waterfowl and other migratory birds (U.S. Environmental Protection Agency, 2011b).

Coastal and ocean resources and coastal communities face unique challenges associated with a changing and changed climate (Nelson and others, 2011). Maintenance of healthy coastal resources is directly dependent on the freshwater systems that sustain coastal environments. For example, many species are sensitive to temperature and salinity, which are directly influenced by weather patterns and freshwater inputs. Temperature and salinity also can influence the frequency and persistence of algal blooms (red tides, cyanobacterial blooms, pfiesteria, etc.).

Key coastal issues that are likely to be impacted by climate change include:

- **Extreme events:** Changes in the intensity, duration, and number of hurricanes, tropical storms, and intense coastal low pressure systems may increase coastal hazards and affect portions of the coast previously unimpacted by these systems.
- **Emergency Response Infrastructure:** Changes in hazards as hurricanes and other coastal storms increase in intensity and shoreline erosion continues (Hapke and others, 2010);
- **Drinking water quality:** Changes in the condition of coastal freshwater aquifers and drinking water supplies that are vulnerable to risks as sea levels rise or salt water intrusion increases;
- **Sea level changes:** Rising sea levels and changes in storm frequency, intensity, and duration that affect the design, operation, and management of water infrastructure (drinking water systems, water storage, wastewater and stormwater management and reuse) (for example, Intergovernmental Panel on Climate Change, 2007b);
- **Coastal habitats:** Alterations in estuarine and coastal habitats at risk of inundation as sea levels rise (Intergovernmental Panel on Climate Change, 2001);
- **Hypoxia:** The extent of hypoxia (lowered oxygen levels) and "dead zones" in the Gulf of Mexico, Chesapeake Bay, and other water bodies as contaminant loads change; and
- **Acidification:** The quality of coastal and ocean fisheries and habitat, such as coral reefs, at risk due to warmer waters and ocean acidification.

The National Assessment of Coastal Vulnerability to Sea Level Rise has classified United States coastal environments to develop a comparative index of the potential for physical shoreline changes in response to sea level rise (fig. 2; Thieler and others, 1999–2000). High-vulnerability areas tend to be barrier islands with small tidal ranges, large waves, a low coastal slope, and high historical rates of sea-level rise.

The recent National Coastal Commission Report (NCCR) (coordinated through the USEPA, NOAA, USGS, USFWS, coastal States, and the NEPs) rated the overall condition of coastal environments as fair (U.S. Environmental Protection Agency, 2008). From a water-quality standpoint, the National Coastal Commission develops a net score based on five indices of ecological condition (U.S. Environmental Protection Agency, 2008):

- Water-quality index (including dissolved oxygen, chlorophyll a, nitrogen, phosphorus, and water clarity);
- Sediment quality index [including sediment toxicity, sediment contaminants, and sediment total organic carbon (TOC)];
- Benthic index;
- Coastal habitat index; and
- A fish tissue contaminants index.

An overview of the national coastal condition scorecard is shown in figure 3. As of 2008, 18 percent of estuarine waters were considered to be impaired for fishing, based on the prevalence of fish tissue contaminants (U.S. Environmental Protection Agency, 2008).

Examples of up-to-date climate-relevant information, data, maps, and models that are needed to make decisions about the management of coastal and ocean resources and the ecosystems they support include:

- Estimates of relative sea level change and storm-surge hazards to determine how tidal fluctuations and sea-level rise will impact coastal environments, communities, and their water infrastructure;
- Geospatial data on the locations and characteristics of wetlands and their resiliency to sea-level rise to predict the effects on coastal wetlands and adjacent coastal resources of a changing climate;
- An understanding of coastal ecosystem responses to changing upland hydrology, flood frequencies, and water-quality conditions; and
- Hydrodynamic models to predict the likely extent and consequences of saltwater intrusion under various conditions and water management practices (groundwater recharge, water allocations, ocean outfalls, and deep well injection).

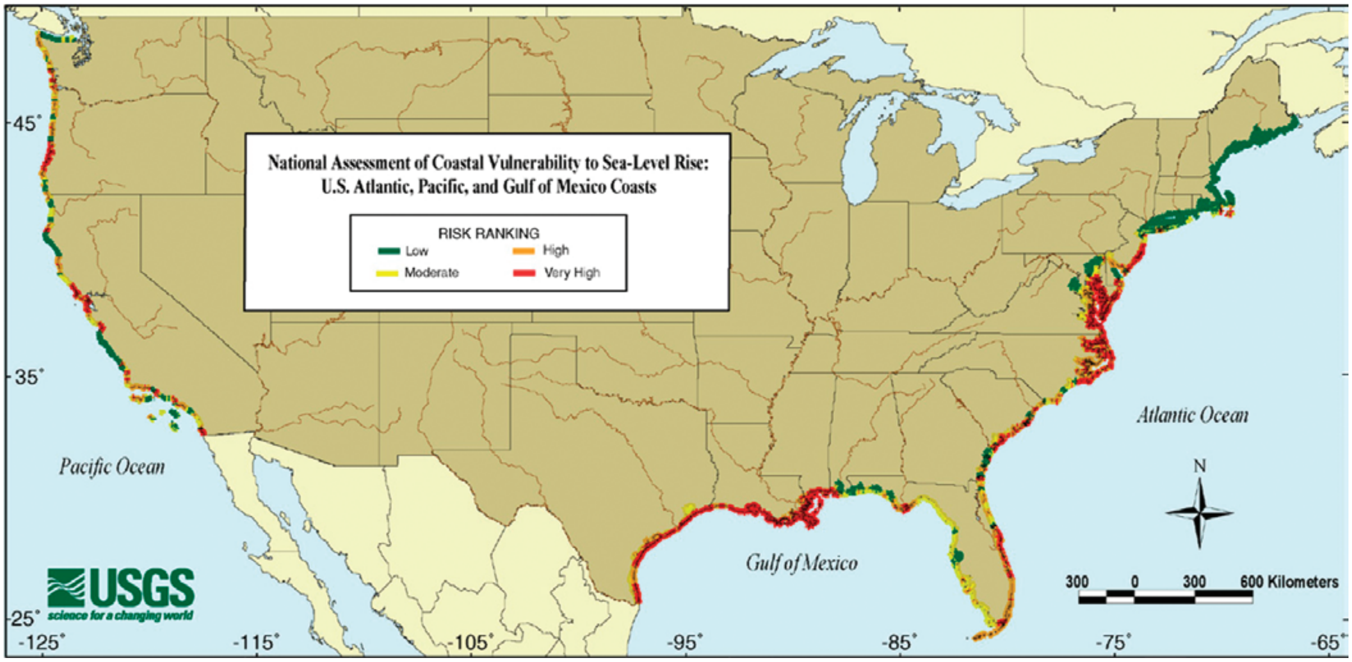


Figure 2. Relative vulnerability of coastal areas to seal level rise (Thieler and others, 1999–2000).

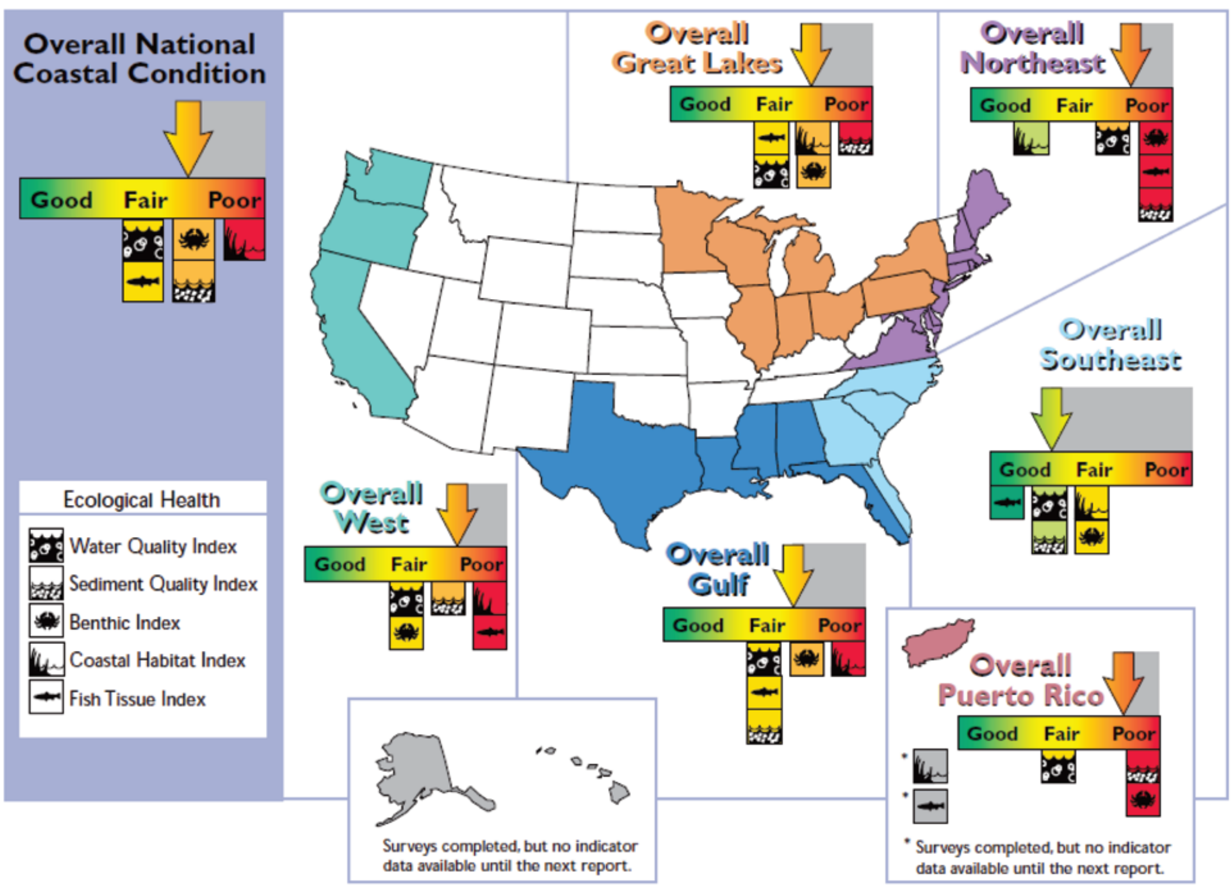


Figure 3. Overview of coastal condition scorecard (U.S. Environmental Protection Agency, 2008).

Review Elements

Section 9506 identifies six interrelated review elements (Appendix A):

- Assess adequacy of current hydro-climatological observation networks;
- Identify data gaps in current water monitoring networks;
- Improve data management to increase utility of information that is collected and efficiency of data acquisition and reporting;
- Establish a data portal to enhance access to water resource data across agencies;
- Facilitate the development of hydrologic and other models to integrate data that reflects groundwater and surface water interactions; and
- Apply hydrologic models to resolve water resource problems including improvement of ecological resiliency.

Each review is discussed in turn, using information contributed from agencies and groups that produce data, manage networks, develop and maintain models, and operate data portals, or have plans to do so. It is important to recognize that each of the six review elements encompass significant ongoing activity both inside and outside of the Federal government. Because of the general overlap of elements 1 (adequacy of networks) and 2 (gaps in current networks), these two elements are combined for the purposes of this review.

There is substantial complexity in monitoring and observing systems and the manner in which data from these systems are combined to increase understanding of past, current, and future conditions and trends. Some of the interconnections among the review elements are illustrated in figure 4. As shown, networks are used to organize and map individual data elements. Integrated networks can be compiled and shared through data portals. Models require data for development and application. Mapping and modeling tools build upon historical data to evaluate past trends and to project the range of outcomes of future climate, land-use, and water-management scenarios on water resources and the human and aquatic systems they support. The extent to which the physical hydrologic system, as well as observations, data, modeling, mapping, and decision-making are interconnected highlights the importance of coordination, collaboration, and communication. Some initial efforts to integrate data are underway through a variety of formal and *ad hoc* groups, such as the USGCRP, the National Water-quality Monitoring Council, and the Consortium for the Advancement of Hydrologic Sciences, Inc. (CUAHSI).

> "The only way to figure out what is happening to our planet is to measure it, and this means tracking changes decade after decade and poring over the records. A point of diminishing scientific returns has never been realized in what is now known as the "Keeling Curve," the Mauna Loa CO_2 record."
>
> *Ralph Keeling, 2008*

Background

Numerous reports from a wide range of organizations and constituencies have called for strengthening the Nation's environmental monitoring networks. The Congressional Research Service (2009), in a review of 1973 National Water Commission findings, noted that "Few would disagree with or reject a recommendation for more and better water-quality monitoring . . . environmental monitoring generally, and water-quality monitoring specifically, receive less priority and funding than do regulatory or capital improvement programs." Tracy Meehan, The Cadmus Group, has said, "Data and water monitoring, both as to quantity and quality, are foundational to water management especially in an era in which the focus has moved away from an almost exclusive preoccupation with end-of-the-pipe point source dischargers to a broader concern with watersheds, generally, and the physical and biological integrity, not just chemical, of our nation's aquatic resources (Meehan, 2010)."

The Johnson Foundation (2010), recognizing the role of science in water-resources management called for the generation of "sound science that accounts for the dynamic nature of freshwater systems and our emerging understanding of climate change impacts on water that can be shared in real-time to inform mitigation and adaptive management strategies." Furthermore, the Foundation recommended "that Federal agencies, especially those within the U.S. Department of the Interior, expand existing nationwide freshwater quality and quantity monitoring and data collection networks and outfit them with cutting-edge technology that enables rapid data analysis and real-time data sharing. The installation of additional streamgages, water meters, groundwater monitoring wells, and better estimates of consumptive use are of paramount importance for the effective management of available water supplies." The Water Environment Federation (2010) notes that "Water resource managers must also adapt to new information, consistently refining their approach to sustainability. They must continually incorporate locally relevant data into long-range planning and recognize that climate change is altering long-held beliefs about hydrological norms."

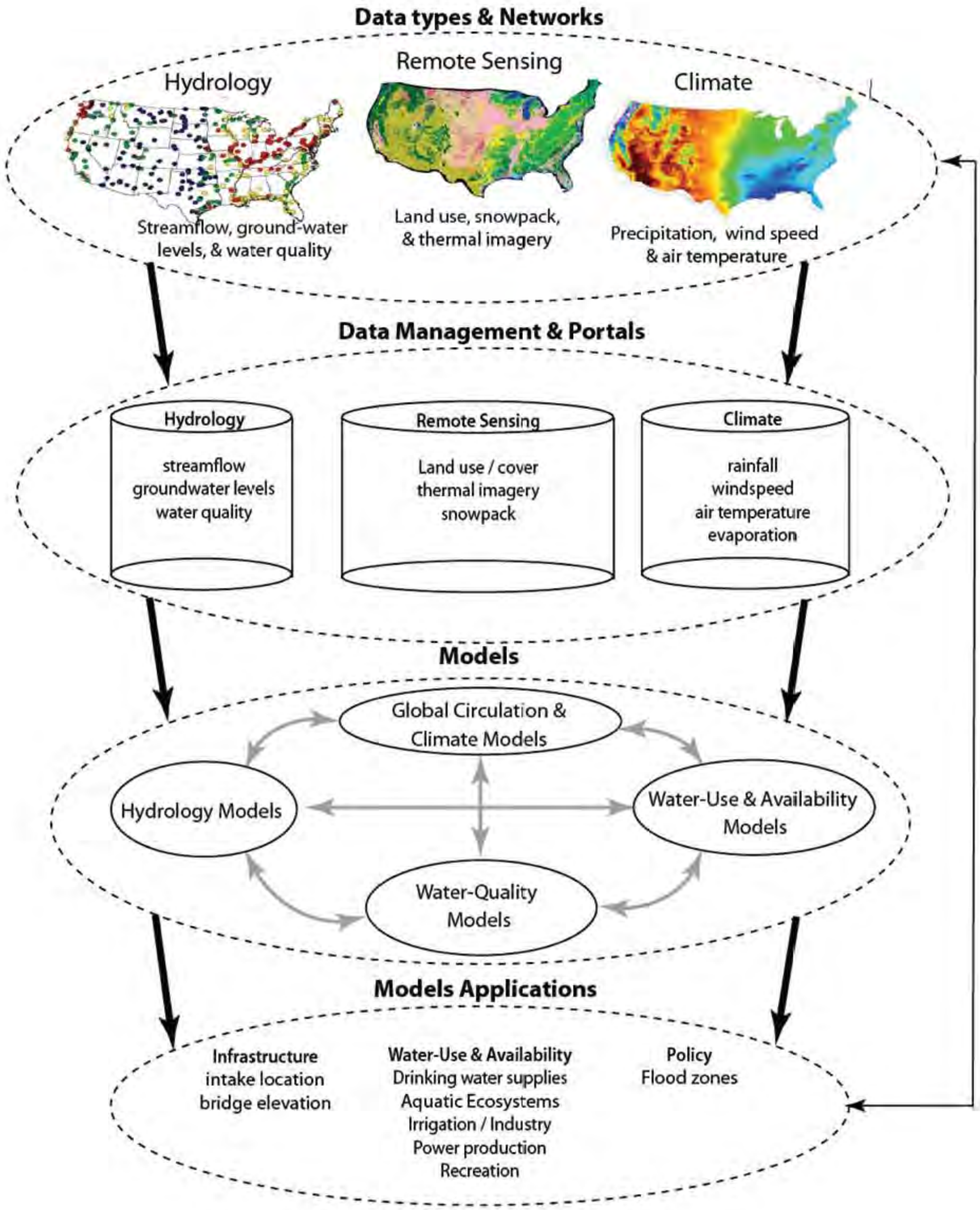


Figure 4. Examples of interconnections among data, models, and model applications for decision-makers.

The Climate Change and Water Working Group (CCAWWG) (National Oceanic and Atmospheric Administration, 2008) is an interagency group that has been working to identify critical gaps relevant to climate change adaptation. Several recent reports (Brekke and others, 2009, 2011) have highlighted the need for collaborative efforts across the water management and scientific communities to develop, test, and apply new methods, tools, and capabilities. Key goals include (1) enhanced monitoring and data collection, and (2) improved decision-making under uncertainty.

In an October 2010 report to the President, the Interagency Climate Change Adaptation Task Force (2010) recommended that water resources management be enhanced in response to a changing climate by strengthening data and information systems. This report also called for development of a *National Action Plan* addressing management of freshwater resources in a changing climate. The draft *National Action Plan* (*http://www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation*) describes a number of actions related to improvement of data and information for adaptation to climate change.

There also is wide recognition that better coordination of environmental data collection would benefit the Nation. The U.S. Governmental Accountability Office (GAO) (2004) noted that 15 agencies collect water-quality data, and that hundreds of other organizations collect these data, in contrast to the relatively few agencies that collect water quantity data. GAO identified several barriers to improved coordination, including data-quality objectives, methods, awareness of others collecting the same type of data, and low priority of coordination. The Subcommittee on Groundwater (2009) addressed the issue of coordination by proposing a mechanism whereby groundwater data collected by various entities could be readily exchanged through the use of common definitions and data catalogs.

In May 2011, the National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, and U.S. Geological Survey signed a memorandum of understanding better align agency programs to support integrative and adaptive water management. The partnership will address the goals of the Integrated Science and Services initiative (*http://nws.noaa.gov/oh/docs/IWRSS_1p_summary.pdf*), with the objective of building a Federal Support Toolbox for integrated water-resources management. The U.S. Geological Survey Water Census (*http://pubs.usgs.gov/fs/2007/3112/fs2007-3112.pdf*) will support this initiative, and will work across Federal, State, Tribal, and local agencies to integrate water-resources information with the goal of developing detailed water budgets for most river basins in the U.S.

Adaptive management has emerged as one approach to managing water resources and the ecosystems they support in the face of a variety of uncertainties, including climate change. Endangered species are being managed adaptively in Upper Colorado River, the Delaware River, the Missouri River, the San Joaquin/Sacramento Bay-Delta, the Platte River, and elsewhere. Adaptive management can only be successful when supported by a robust data-collection and analysis program, or as the Council on Environmental Quality (2003) suggests, “monitor and adapt.”

Review Elements 1 and 2: Assess Current Hydroclimatological Observation Networks and Identify Data Gaps

Review Element from Section 9506:

> *“to assess the extent to which the conduct of measures of streamflow, groundwater levels, soil moisture, evapotranspiration rates, evaporation rates, snowpack levels, precipitation amounts, and glacier mass is necessary to improve the understanding of the Federal Government and the States with respect to each impact of global climate change on water resources…”*
>
> and
>
> *“to identify data gaps in current water monitoring networks that must be addressed to improve the capability of the Federal Government and the States to measure, analyze, and predict changes to the quality and quantity of water resources, including flood risks, that are directly or indirectly affected by global climate change…”*

For simplicity of presentation, review elements 1 and 2 have been subdivided into six sub-elements:

- Streamflow;
- Groundwater levels;
- Soil moisture and evapotranspiration;
- Precipitation amounts, snowpack, and glacier mass;
- Water quality and ecosystem conditions; and
- Water withdrawals and consumptive use.

Finding 1: Broad Support for Improved Monitoring Systems. There is broad and continuing support from a wide constituency to sustain and strengthen the Nation’s hydroclimatic monitoring systems, including research to support those systems. In particular, adaptive management and water-resources planning tools are only effective when supported by strong data networks.

Significant efforts are devoted to the measuring and monitoring of various attributes of water resources. In some cases, however, there is a lack of coordination among the various efforts because of differing data-collection purposes, methods, and data-quality objectives. Differences in the content and interoperability of data networks reflect current and historic funding levels, programmatic history, agency culture, technology, and the priorities of the organization(s) that collect and manage the data. Regardless of these differences, scientists and decision-makers often combine disparate data sets to develop models and conduct analyses necessary for the management of the Nation's water resources.

Streamflow

Surface waters (streams, rivers, lakes, and reservoirs) serve as a source of drinking water to more than 170 million Americans and supply over 80 percent of the water withdrawals in the United States (Kenny and others, 2009). Much of the Nation's treated municipal, domestic, and industrial water is returned to surface waters along with irrigation return flows, and stormwater runoff. Surface waters provide important aquatic habitats and maintain the viability of commercially valuable fisheries, protected species and aquatic ecosystems. Surface waters also generate tremendous economic benefit through support of agricultural irrigation, tourism (fishing, canoeing, rafting, etc.), navigation, power production, and other industrial freshwater needs. However, changes in the natural flow and thermal regime of rivers, coupled with waterborne contamination have degraded the availability and quality of critical water resources and the ecosystems they support (U.S. Environmental Protection Agency, 2010b).

Until recently, it was assumed that future streamflow conditions (flow magnitude, seasonal distribution of flows, occurrence of floods and droughts, etc.) could be estimated from historical data. The idea that the past streamflow conditions are a proxy for the future is based on the statistical property of stationarity (Milly and others, 2008). However, as natural systems respond to changing climate and other types of global change (for example, land and water management practices), and as we gain improved understanding of the inherent long-term variability in natural systems, there is increasing uncertainty about estimates of future streamflow conditions obtained using currently available models and statistical methods. Nevertheless, continuous, long-term records of streamflow are indispensable to the estimation of future streamflow conditions, but the number of long-term streamflow gages continues to decline (fig. 5).

The USGS operates more than 7,500 streamgages (fig. 6; Norris, 2009) in cooperation with about 850 Federal, State, Tribal, and local partners. In most cases, streamflow observations are made at 1-minute to 1-hour intervals (U.S. Geological Survey, 2011b) and are transmitted via satellite to Federal [for example, National Weather Service (NWS)] and local users using the Internet. The immediate availability of streamflow data (often reported within 1 hour of collection) helps decision-makers respond to emergency situations and also address day-to-day management of irrigation systems, water supply and wastewater facilities, reservoirs, canals, and navigation systems. For example, NWS River Forecast Centers (RFC's) (U.S. Geological Survey, 2011c) use streamflow data to provide short-term (about 7–day) flood forecasts, as well as monthly to seasonal water availability forecasts. The compilation of long-term streamflow datasets (U.S. Geological Survey, 2011c) provides aggregated data that are used to design water systems and infrastructure, calibrate forecast models, and evaluate streamflow response to climate change (McCabe and Wolock, 2002).

Almost half of the funding for the current streamgage network comes from State, regional, local, and Tribal partners (Norris, 2009). As a result, the availability of funding tends

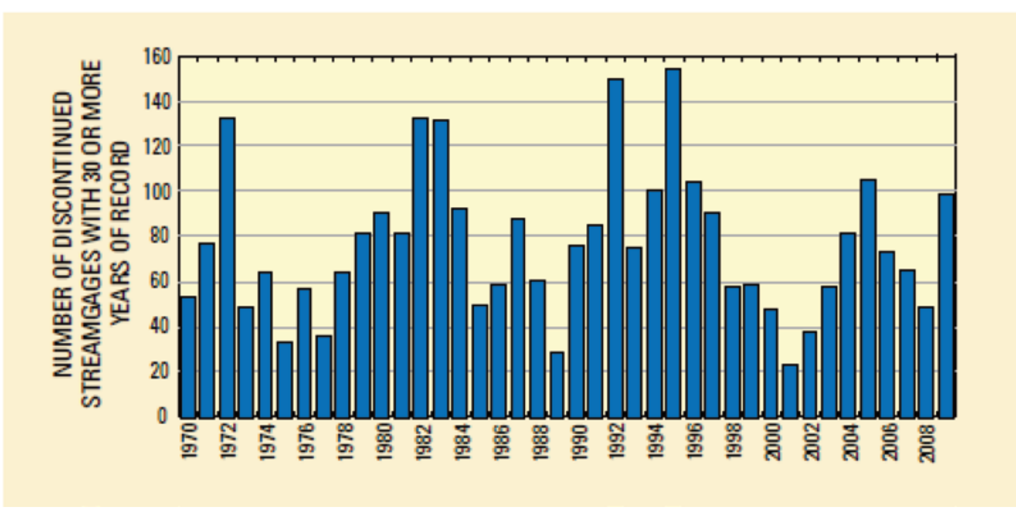


Figure 5. Number of discontinued U.S. Geological Survey streamflow gages with 30 or more years of record, 1970–2009 (Norris, 2009).

to fluctuate from year to year, leading to instability in the network.

The National Streamflow Information Program (NSIP) (U.S. Geological Survey, 2011d) was initiated in 2003 in response to Congressional and stakeholder concerns about (1) the decrease in the number of operating streamgages, including a disproportionate loss of streamgages with a long period of record (fig. 5); (2) the inability of the USGS to continue operating high-priority streamgages in an environment of reduced funding through partnerships; and (3) the increasing demand for streamflow information due to emerging resource-management issues and new data-delivery capabilities (Norris, 2009). In 2009, NSIP was authorized as part of Section 9507 of PL 111-11, with a full implementation goal of 2019. The National Streamflow Information Program was begun in 2003 with 5 program goals (U.S. Geological Survey, 2011e). These goals are to (1) develop a stable streamgaging network; (2) conduct intensive data collection during floods and droughts; (3) conduct regional and national streamflow assessments; (4) improve data delivery; and (5) invest in methods development research. Current progress toward meeting the goals include 15 percent of the stable streamgaging network in place with some improvements in data delivery.

In addition to the USGS network, a number of smaller streamgage networks are operated by other Federal agencies and States. The U.S. Army Corps of Engineers (USACE) operates a network of gages, many of which provide water level only, in support of their civil works programs. Information generally is available by Corps District (for example, St. Louis district (*http://mvs-wc.mvs.usace.army.mil/dresriv.html; http://www.mvp-wc.usace.army.mil/dcp/*), or for all Corps sites (*http://rivergages.mvd.usace.army.mil/WaterControl/new/layout.cfm*). Similarly, the U.S. Fish and Wildlife Service collects streamflow information on some of their refuges (for example, *http://alaska.fws.gov/water/monitor.htm*), as do the National Park Service (NPS) (*http://www.nature.nps.gov/water/*), and the U.S. Forest Service (for example, see Water at *http://www.fs.usda.gov/rds/archive/datacatalog/*), each for agency-specific purposes. Some States also operate their own streamflow networks. For example, Colorado maintains a network of gages to assist in administration of water rights (*http://www.dwr.state.co.us/SurfaceWater/Default.aspx*). The West Virginia Water Gaging Council maintains a web page from which users can access streamflow, flood warning, precipitation, and groundwater data collected by a variety of agencies and organizations (*http://wvwgc.wvca.us/*). Tremendous benefits could be gained for the Nation if these disparate data sets were more broadly available and included information on methods of collection, quality, and accuracy.

The amount of water stored in lakes and reservoirs is directly linked to streamflow because of the effect of dam releases on flows, as well as losses from incoming streamflow to evaporation. Reservoir lake-level data, when converted to water volume, provide important information to water managers regarding availability of short-term (days to months) future water supplies, dam operation, downstream navigation, and maintenance of instream flows.

Finding 2: Streamflow Data. The National Streamflow Information Program was begun in 2003 with 5 program goals. These goals are to (1) develop a stable streamgaging network; (2) conduct intensive data collection during floods and droughts; (3) conduct regional and national streamflow assessments; (4) improve data delivery; and (5) invest in methods development research. Current progress toward meeting the goals include 15 percent of the stable streamgaging network in place with some improvements in data delivery.

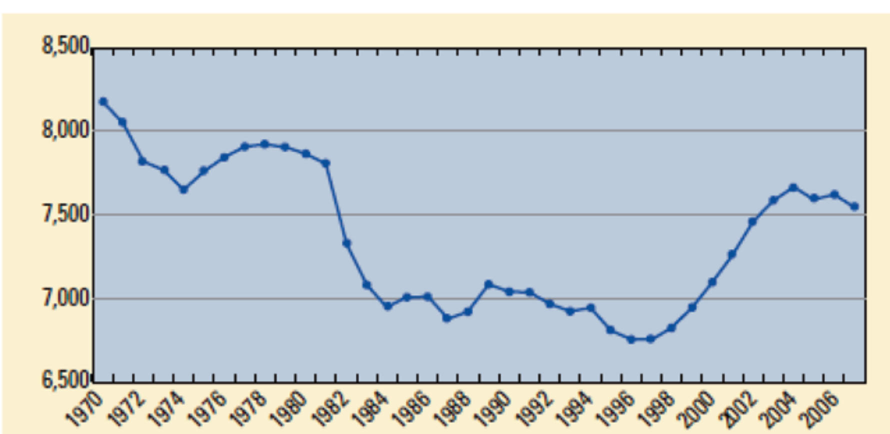


Figure 6. Number of active streamgages in U.S. Geological Survey network, 1970–2007 (Norris, 2009).

Finding 3: Streamflow Information Coordination. Streamflow information is collected by a variety of Federal and State agencies, generally for agency-specific purposes. Tremendous benefits could be gained for the Nation if these disparate data sets were more broadly available, interoperable, and included information on methods of collection, quality, and accuracy.

The USACE (*http://www.ndc.iwr.usace.army.mil/*), and the Bureau of Reclamation (BoR) (*http://www.usbr.gov/lc/region/g4000/hourly/levels.html*) provide lake level data on most of the reservoirs which they operate, with some of the lake level measurements made by the USGS. Similar information is reported by the Tennessee Valley Authority (TVA) (*http://www.tva.com/river/lakeinfo/index.htm*). Data are available at varying intervals, from hourly to monthly.

Although Federal projects (USACE, TVA, BoR) account for the majority of water storage in the U.S., a number of river systems are managed by private entities (for example, the Catawba–Wateree River in North and South Carolina, managed by Duke Energy, and the Alabama River, managed by Alabama Power). Numerous small impoundments are managed by the Natural Resources Conservation Service (NRCS), irrigation districts, and water utilities, some of which have continuous lake level information. However, limited data exist for many natural lakes.

Water resource managers also need knowledge about reservoir and lake volumes in conjunction with water-level monitoring in order to estimate reservoir contents at any particular time. Sediments tend to accumulate in lakes and reservoirs, reducing the volume available for storing water. In addition to affecting the available volume, trapped sediments in reservoirs can be an important sink for carbon and also may harbor contaminants and pathogens (Stallard, 1998). Precipitation patterns (form, intensity, and frequency), fires, intense storms and droughts, along with changes in hydrology, land use, and land management affect the amount of sediment transported into reservoirs. The Reservoir Sedimentation Database (RESSED) (U.S. Geological Survey, 2009b), started in 2009, is a preliminary effort to develop a dynamic database of reservoir volume. Bathymetric reservoir data are used to estimate the volume of the underwater environment. NOAA provides bathymetric data on coastal waters (National Oceanic and Atmospheric Administration, 2011e) and collaborates with the Canadian Hydrographic Service (CHS) to provide data on the Great Lakes, but measurements of other freshwater systems have declined substantially (fig. 7; Ackerman and others, 2009).

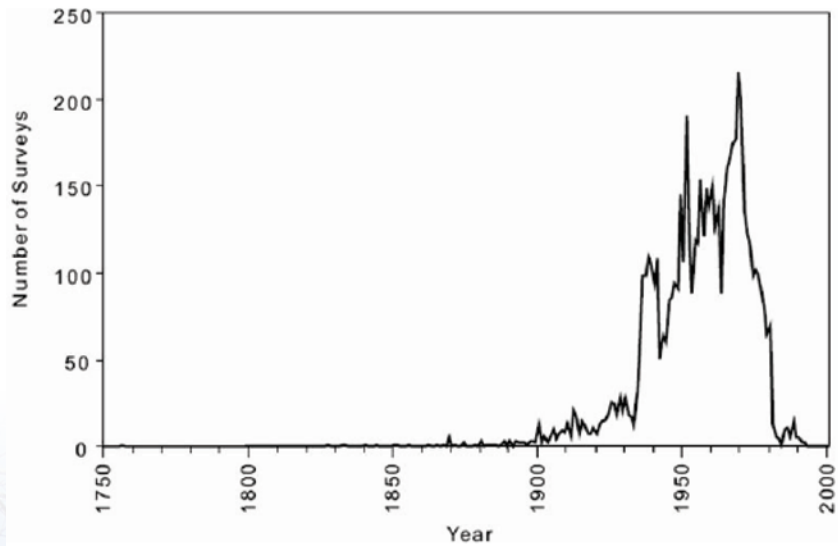
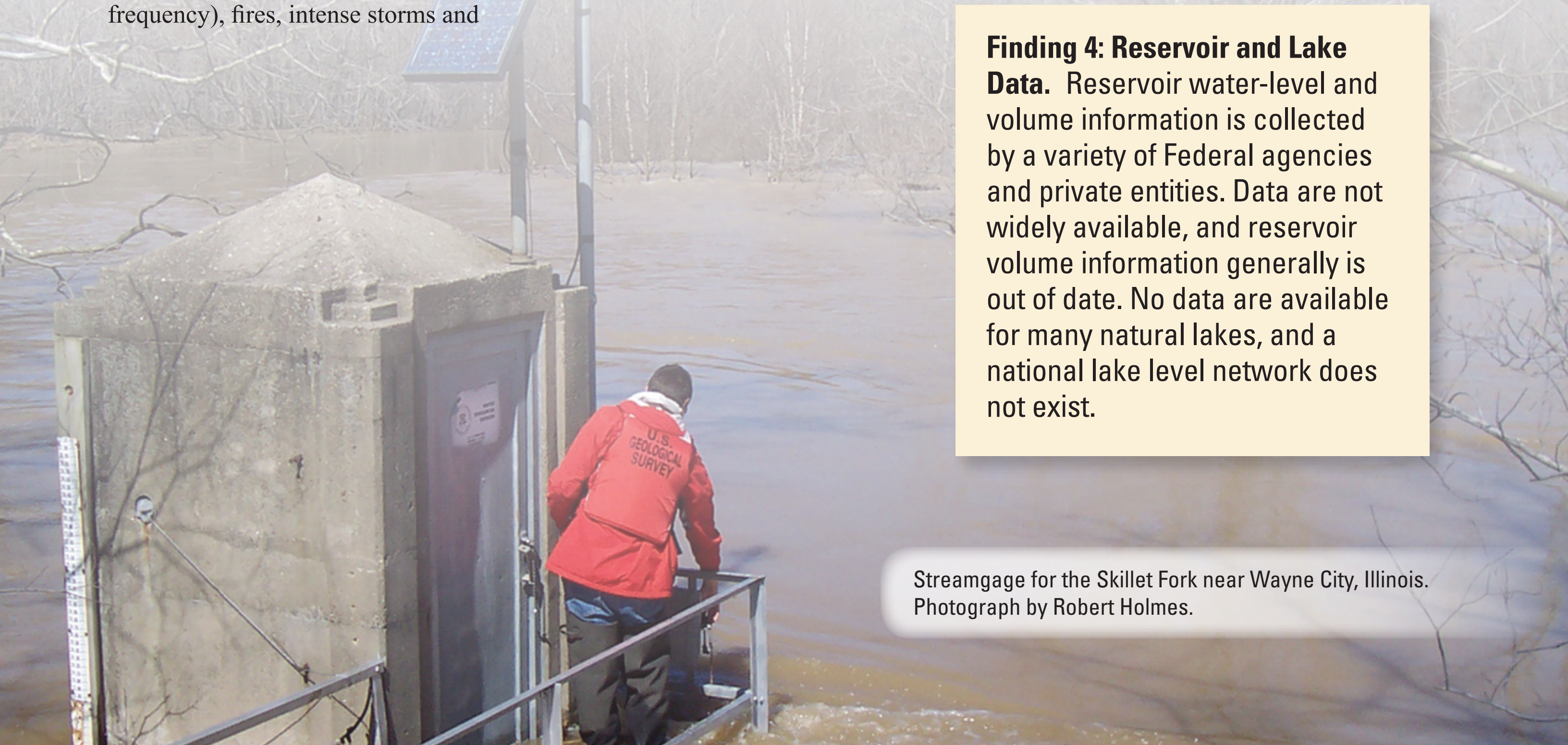


Figure 7. United States reservoir sedimentation surveys, 1750–2000 (Ackerman and others, 2009).

Finding 4: Reservoir and Lake Data. Reservoir water-level and volume information is collected by a variety of Federal agencies and private entities. Data are not widely available, and reservoir volume information generally is out of date. No data are available for many natural lakes, and a national lake level network does not exist.



Streamgage for the Skillet Fork near Wayne City, Illinois. Photograph by Robert Holmes.

Groundwater Levels

Measurements of groundwater levels are used to determine water availability within specific aquifers and to assess overall climatic conditions. Groundwater is the primary source of public water supply for about 130 million Americans, including about 97 percent of the rural population (U.S. Geological Survey, 1995; Dennehy, 2005). Approximately 42 percent of irrigation water supplies are withdrawn from groundwater (Hutson and others, 2004). Additionally, groundwater sustains and replenishes rivers and streams during the hottest and driest parts of the year, providing critical flow to aquatic ecosystems. Groundwater accounts for a large percentage of the total flow in most streams, with as much as 80 percent of streamflow originating from groundwater in some parts of the Nation (Winter and others, 1998). As locations for additional reservoirs become limited and availability of water from the Nation's streams becomes increasingly scarce, withdrawals from groundwater are likely to increase (Hutson and others, 2004); even brackish groundwater is seen as a potential future water supply. In many areas, including California and the southeastern U.S., increases in groundwater use during surface water shortages have been dramatic. Data and models are needed to better understand the implications of precipitation variability, and withdrawals on groundwater availability and, because of the tight coupling of surface and groundwater, on streamflows and aquatic ecosystems.

Climate change, changes in agricultural practices, and energy development likely will introduce other impacts on groundwater systems, with cascading effects on the rate and intensity of pumping to support local water needs (irrigation, frost prevention, fire-fighting, urban uses). For example, intensive short-term demands on groundwater within agricultural regions in response to freezing or drought conditions has led to rapid lowering of instream flows and aquifer levels with subsequent generation of sinkholes, particularly in karst regions (Tihansky, 1999). Climate change adaptation and mitigation efforts also can spur development of competing water uses in a region for activities such as biofuel production, hydraulic fracturing, mineral and fuel resource extraction, industrial activities, or agriculture. Recent studies have suggested that groundwater depletion is contributing to sea level rise through aquifer compaction and land subsidence (Wada and others, 2010).

The USGS maintains and monitors more than 20,000 observation wells in cooperation with State and local agencies, with monitoring frequencies ranging from hourly to annually, or less infrequently. Industries and municipalities also operate and maintain wells. In addition to data on water levels, water quality and precipitation data are collected at many sites. Observation and monitoring wells also are used to evaluate underground sources of drinking water, to support the Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA), for mineral and energy resource extraction, to develop aquifer storage and recovery or groundwater recharge programs, and for groundwater remediation projects. Nevertheless, according to the U.S. Governmental Accountability Office (2004), no Federal agencies are collecting groundwater level data on a national scale.

Water levels are recorded from an irrigation well in Laramie County, Wyoming.

A complete inventory of all active (or abandoned) wells does not exist. In fact, there is wide variability in the amount of information available, depending on how active State governments and local water districts are in managing groundwater rights and well drilling activities. Although a complete inventory is not a necessity for effective water-resources management, such an inventory would be useful for protecting groundwater resources and for designing data collection networks. Certainly, information on all future wells should be made available through a common framework. Limited analyses of the interrelationships among water quality, water levels, and well pumping practices have been conducted. These types of analyses generally require application of complex groundwater models founded on good data and a reasonable representation of the hydrogeology.

Over the past few years, concerted efforts have been made to develop a Climate Response Network (CRN, which is distinct from NOAA's Climate Reference Network) to measure response of the groundwater system to climate variations (U.S. Geological Survey, 2011f). The CRN is designed to monitor groundwater fluctuations in unstressed aquifers, as these systems often can provide early indications of drought. While modest progress has been made, the CRN currently includes sites in only 60 percent of the Nation's 42 principal aquifers (U.S. Geological Survey, 2003) and in fewer than half of the 366 NOAA climate divisions in the United States and Puerto Rico (Cunningham and others, 2007). In addition, when multiple aquifers are present in a given climate division there is a need to provide additional monitoring sites. Such a network, one climate response well per principal aquifer in each climate division of the U.S., might be considered a minimum design for a CRN. The CRN, however, is not designed to monitor the effects of groundwater withdrawals on groundwater availability.

Section 9507 of PL 111-11 directs the Secretary of the Interior to "develop a systematic groundwater monitoring program for each major aquifer system located in the United States." The legislation contains a number of key features, including "expanding the network of monitoring wells to include each climate division." Appropriations for the groundwater monitoring network are authorized for 2009–2023. The Subcommittee on Groundwater (SOGW) of the Federal Advisory Committee on Water Information recently completed a design for a National Ground-Water Monitoring Network (Subcommittee on Groundwater, 2009). The proposed network is a compilation of wells from existing State and Federal monitoring activities, and was designed to focus on monitoring the most productive aquifers. The final design will vary by aquifer, but likely will specify a minimum number of wells to achieve a desired monitoring density. The network would monitor both stressed and unstressed systems (fig. 8), with targeted monitoring in areas of concern (areas of contamination or depletion). The National Network design also calls for development of a data-management system with applications that facilitate the retrieval and display of data in dispersed databases. The network currently (2011) is being piloted in six States (Advisory Committee on Water Information, 2011): Illinois-Indiana, Minnesota, Montana, New Jersey, and Texas.

Finding 5: Groundwater-Level Monitoring. The Advisory Committee on Water Information's Subcommittee on Groundwater has developed a comprehensive national groundwater monitoring network that could provide data and information necessary for planning, management, and development of the Nation's groundwater resources in a sustainable manner. This network was authorized in Section 9507 of PL 111-11.

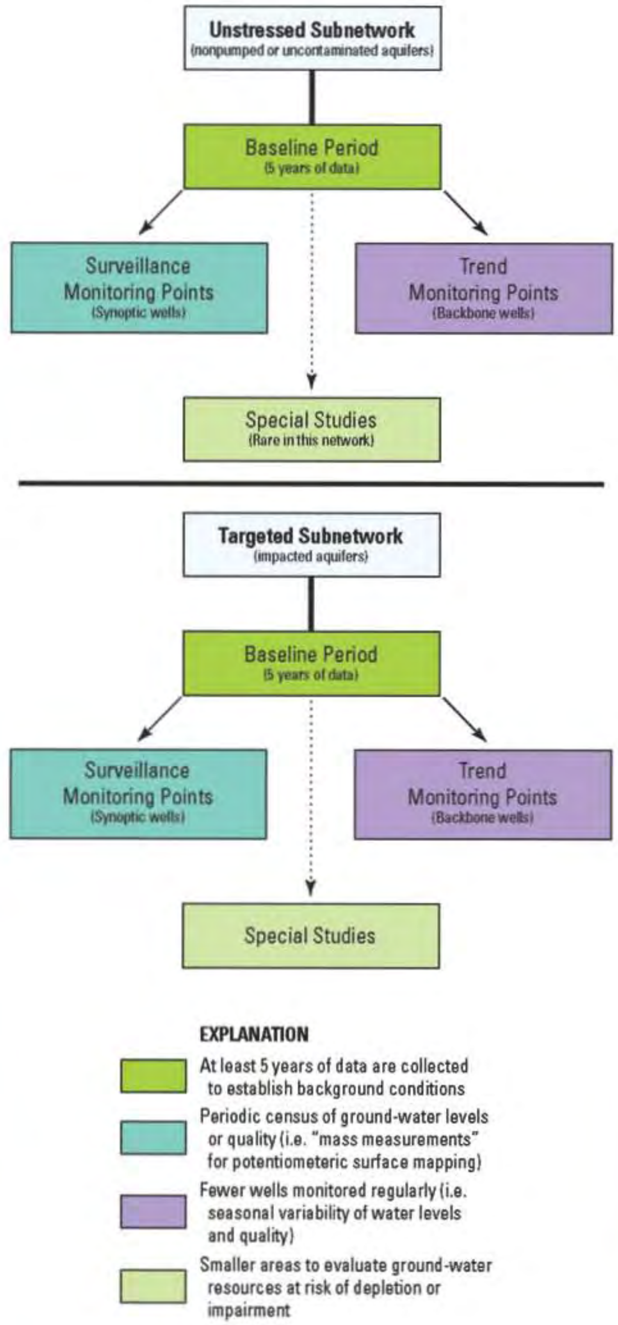
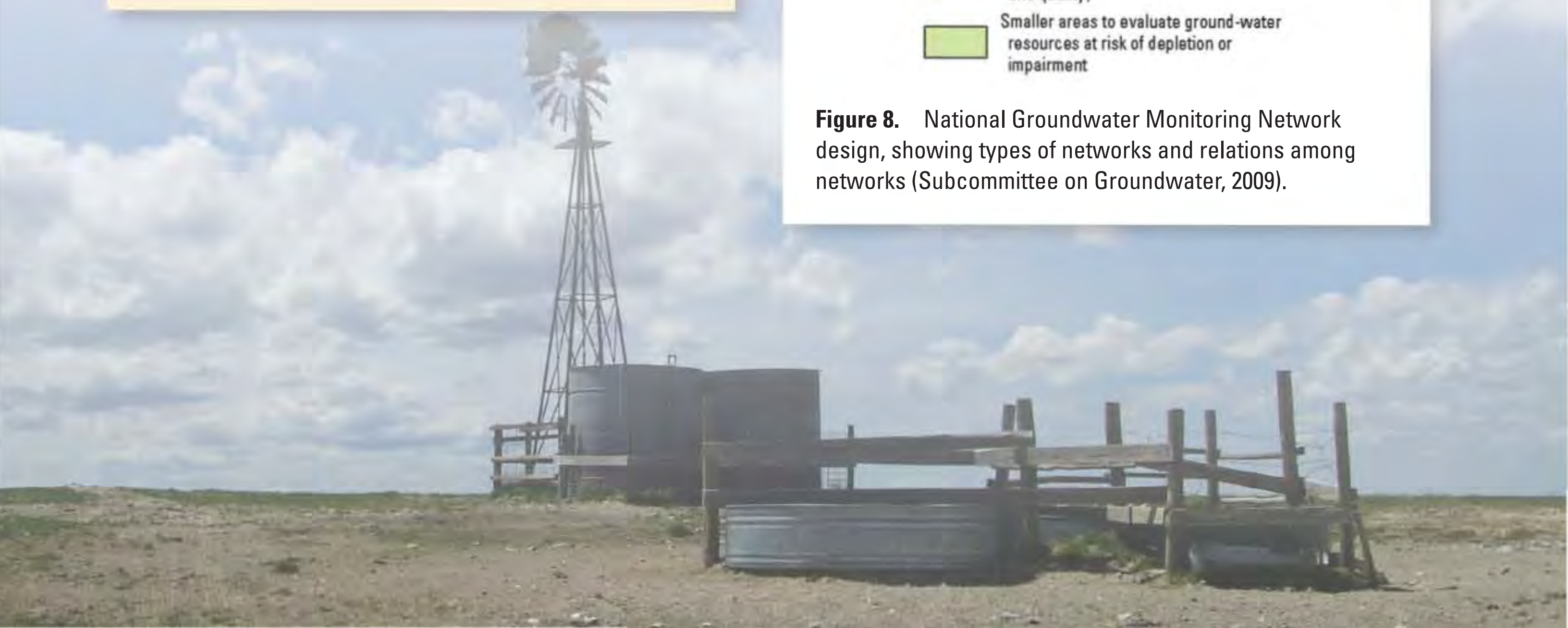


Figure 8. National Groundwater Monitoring Network design, showing types of networks and relations among networks (Subcommittee on Groundwater, 2009).



Soil Moisture and Evapotranspiration

Soil moisture is critical for agricultural crop production. With climate change and the concomitant changes in the length of the growing season, farmers' water use practices will need to adapt to changes in crop requirements, available precipitation, and the rate of evapotranspiration (Intergovernmental Panel on Climate Change, 2007c). The amount of moisture stored in the soil is directly related to the balance between water saturation (through rainfall or irrigation) and evapotranspiration, or the amount of water released to the environment through the growth of plants, trees, and vegetation. These factors, in conjunction with land use patterns and local hydrology influence the rate and extent of groundwater recharge and generation of runoff.

Changes in soil moisture are likely to vary, depending on watershed characteristics, soil properties, temperature, and the size and the role of the landscape in storing water (Furniss and others, 2010). The local effects of climate change on soil moisture are complex and interdependent on multiple factors. Soil characteristics dictate the relative capability of a soil to store water, influencing the magnitude and persistence of soil moisture. Climate change can affect soil moisture through changes in precipitation and air temperature. The quality of irrigation water, particularly the salt and mineral content, also affects short-term and long-term soil moisture. Infiltration capacity and water-holding capacity of many soils are influenced by the frequency and intensity of freezing. The seasonality of soil moisture is important for sustainable agriculture and often is the controlling factor in whether irrigation water needs to be applied to produce crops. For example, in the West and Midwest, soils are likely to dry earlier in the year with increasing air temperatures, imposing stress on existing vegetation and leading to changes in the diversity of native vegetation and insect outbreaks. Changes in the timing of snowpack runoff also may affect the seasonality of water availability. Changes in the length and timing of the frost-season affect the survival and proliferation of insect pests and the migration patterns of wildlife, all of which affect ecosystems and soil vitality. Increased decomposition rates from higher temperatures will deplete soil organic matter more rapidly (Furniss and others, 2010), and changing air and soil temperatures will affect the rate of consumptive water use.

Soil moisture is a significant input parameter for meteor-ological, drought and rainfall-runoff forecasts. The 2,200 interagency RAWS (Remote Automated Weather Stations) network includes measurements of soil moisture at some stations (Remote Automated Weather Stations, 2011). The NRCS Soil Climate Analysis Network (SCAN) contains 180 sites in 40 States and U.S. Territories at which soil moisture is measured at 5 depths below the land surface (U.S. Department of Agriculture, 2011a). About nine other meteorological parameters also are measured at the sites, and the data collected at SCAN sites provide all of the information required to calculate a reference evapotranspiration value at each site. SCAN coverage is non-uniform throughout the country with some States having only one site, and other States having 10 or more sites. In addition to organized networks, there likely are numerous private soil-moisture data-collection sites operated by landowners to schedule irrigation. These networks are not connected in any useful manner.

The U.S. Climate Reference Network currently consists of 114 stations that record temperature, precipitation, solar radiation, surface skin temperature, and surface winds. These stations are being expanded to track soil moisture and soil temperature at five depths (5, 10, 20, 50, and 100 cm) (National Oceanic and Atmospheric Administration, 2011a). The goal is to implement about 30 additional stations over the next 5 years and provide calibration sites for the National Aeronautic and Space Administration's (NASA) Soil Moisture Active Passive (SMAP) mission, planned for 2014 (National Aeronautic and Space Administration, 2011b). Nevertheless, a comprehensive design for a national soil moisture network has not been completed. The SMAP mission is designed to provide soil moisture data at daily intervals, with a horizontal resolution of about 10 km x 10 km. The SMAP mission, in conjunction with a robust *in situ* network for calibration, could provide adequate soil moisture data for many applications at regular intervals over much of the country.

Evapotranspiration (ET) is the second largest component of the water cycle after precipitation, and ET is one of the primary consumers of solar energy at the land surface. Thus, an important feature of ET is that the process couples the energy budget and the water budget at the land surface. This coupling makes it difficult to correctly model ET in downscaled global climate simulation models (for example, Bae and others, 2011; Mueller, and others, 2011).

ET is very sensitive to a change in land cover and weather. Change in essentially any one of the other meteorological variables (precipitation, air temperature, humidity, solar radiation, wind, barometric pressure, etc.), changes in the character (frequency, duration, intensity, type) of precipitation, changes in vegetation and land cover, and changes in vegetation response to greenhouse gases all can affect ET. Pan

Finding 6: Soil Moisture. Numerous specialized soil moisture networks exist across the Nation, but there is no design for a national soil moisture network. The NASA Soil Moisture Active Passive Mission, planned for 2014, in conjunction with a robust *in situ* network for calibration, could provide adequate soil moisture data for many applications at regular intervals over much of the country if these efforts were implemented in a coordinated manner.

evaporation is measured at many NWS weather stations, as well as at some weather stations operated by other agencies. Pan evaporation is a measure of the potential maximum evaporation if there was no limit on the amount of water available. Pan evaporation is converted to actual evaporation from free water surfaces (that is, lakes and ponds) using a coefficient, which typically ranges from 0.7 to 0.9.

As the global air temperature has increased, one might expect an associated increase in pan evaporation, as higher temperatures provide more energy for evaporation. However, just the opposite has been observed (Roderick and Farquhar, 2002). There are at least three explanations for the observed decreases in pan evaporation: (1) higher humidity giving the atmosphere less capacity to take up water; (2) decreased winds (Vautard and others, 2010); and (3) reduced solar irradiance associated with increased cloud cover and aerosol concentration (Roderick and Farquhar, 2002). Reduced solar irradiance appears to be the best explanation for reduced pan evaporation in all settings around the world (Roderick and Farquhar, 2002). It has been hypothesized that increased cloud cover and aerosols concentrations will be a result of global temperature increases. Increased aerosol concentrations also are a result of atmospheric pollution.

Transpiration can be measured by using thermal sensors to measure sap flow in the stem of plants (Hatton and others, 1995). Transpiration measurements are made in experimental studies, but not routinely. The primary purpose for measuring transpiration is to separate transpiration from evaporation in measurements of ET, as described below.

There is a growing network of ET measurement sites. ET typically is measured using the eddy-covariance method (for example, Lee and others, 2004) , which permits monitoring of carbon, water (that is, ET), and energy flux at a fast time step over the area of the flux tower footprint (about 1 km^2). These measurements are increasingly recognized as an important tool for understanding the terrestrial water and carbon cycle. Nevertheless, "there are very limited direct measurements of actual evapotranspiration over global land areas, while global analysis products are sensitive to the type of analysis and can contain large errors, and thus are not suitable for trend analysis. Therefore, there is little literature on observed trends in evapotranspiration, whether actual or potential" (Intergovernmental Panel on Climate Change, 2007a).

The Ameriflux Network (Ameriflux, 2011) consists of about active 90 sites (fig. 9) that measure ecosystem exchanges of water, energy, momentum, and CO_2 continuously at hourly or shorter time intervals. Ameriflux is part of the global Fluxnet network (*http://daac.ornl.gov/FLUXNET/fluxnet.shtml*) which consists of more than 500 flux towers. Information from sites in these networks is specific to the ecosystem (for example, vegetation type) in which the measurements are made.

Remote sensing provides perhaps the most useful approach for obtaining estimates of ET over large areas. Landsat thermal, visible, and near-infrared data are being used to estimate ET at the field scale (Allen and others, 2007). These data can be used for scheduling crop irrigation, and also have been used to settle water-rights disputes. Further refinements can be made by using flux tower data in combination with remotely-sensed information (Anderson and others, 2007) or by using multiple sensors (Vinukollu, 2011).

Figure 9. Ameriflux sites in the United States at which ecosystem exchanges of water, energy, momentum, and CO_2 are measured continuously at short time intervals (Ameriflux, 2011).

Finding 7: Evapotranspiration. Operational evapotranspiration data can be obtained from remotely sensed information. *In situ* measurements of energy, carbon, and water fluxes above the canopy provide valuable information on water budgets (as well as energy and carbon budgets) and are valuable for improving remotely-sensed evapotranspiration estimates, but the number of such installations is relatively small.

Precipitation Amounts, Snowpack, and Glacier Mass

Precipitation is the primary means by which freshwater resources are replenished. Information about the magnitude and occurrence of precipitation is relevant to a wide range of decisions with significant economic implications, including long term infrastructure investments. Until recently water management and other resource dependent decisions have been made under the assumption that past observed precipitation patterns and magnitudes will continue in the future. The same assumption has been made about the occurrence of floods and droughts. There is evidence, however, that precipitation patterns are changing from those observed during the last 100 years, with some indication that storm intensity has increased (Zhang and others, 2007, Min and others, 2011), although this evidence is not conclusive (Villarini and others, 2011).

There are many uses for precipitation data. Watershed-models based on historical rainfall records are routinely applied to estimate flood frequency at ungaged sites, or sites with short periods of streamflow record. These flood frequency estimates are used to evaluate and design bridges, flood control structures, stormwater management facilities, and other water-related infrastructure in flood-prone areas, as well as to produce Flood Insurance Rate Maps. Data on daily rainfall and interannual variation in precipitation are important to support agricultural operations. Rainfall data are used in National Weather Service flash flood, flood, and streamflow forecasts.

The NWS precipitation frequency estimates (Technical Paper 24, U.S. Weather Bureau, 1953), updated in the early 1960s, have become the *de facto* national standards by virtue of their inclusion or reference in widely used design standards. NOAA's Hydrometeorological Design Studies Center (HDSC) (National Oceanic and Atmospheric Administration, 2011b) began an effort in 2003 to update precipitation frequency estimates, and updated results are available for 19 States. Probable maximum precipitation estimates were developed decades ago (National Oceanic and Atmospheric Administration, 2011c), and NOAA has no plans to update these estimates. Advances in science, monitoring, and information technology provide an opportunity to revisit these estimates and incorporate newer data. A systematic and consistent approach that uses recent data is needed for updating precipitation frequency estimates. Development of a sound basis for a conservative design standard is important in addressing the impacts of a changed and changing climate.

Finding 8: Precipitation Frequency-Duration-Intensity Estimates. A systematic and consistent approach that includes recent data and improved statistical techniques is needed for updating precipitation intensity-duration-frequency estimates.

NOAA manages the Climate Reference Network (114 stations) and the U.S. Historical Climatology Network (1,221 stations) (National Oceanic and Atmospheric Administration, 2011d) networks, which are designed to document temperature and precipitation trends. Of the currently operating 11,400 Cooperative Observer Program (COOP) (National Oceanic and Atmospheric Administration, 2011e) stations, about 5,000 make up the "climate" network (the remaining stations support hydrology requirements). In general, precipitation gages tend to be more numerous in the east, south central, southeast, southwest, and northwest, often co-located with streamgages or installed at or near major metropolitan airports. Although airports are convenient, the continuity and accuracy of the long-term data sets can be inconsistent due to site relocations, instrument changes, and the consequences of encroaching urbanization and related heat island effects. With a few exceptions, the instruments used by NWS cooperative observers have not changed significantly over the past century. Numerous other agencies and group measure precipitation. Included are the USGS (for example, *http://waterdata.usgs.gov/va/nwis/current/?type=precip&group_key=county_cd*), numerous state networks (for example, *http://www.nc-climate.ncsu.edu/map/*), research institutions, and private individuals (for example, Weather Stations at *http://www.wunderground.com/cgi-bin/findweather/hdfForecast?query=20192*).

The NWS NEXRAD system (National Oceanic and Atmospheric Administration, 2011f) revolutionized precipitation reporting on the U.S. NEXRAD provides real-time information in precipitation intensity and other measures. Storm precipitation amounts can be obtained by integrating individual NEXRAD scenes. Data are available at a spatial resolution of 4.4 x 4.4 km, and can be statistically down-scaled to 1.1 x 1.1 km. Radar estimates of precipitation, however, must be regularly calibrated to observations. Calibration schemes account for such variables as season, precipitation type, precipitation intensity, and weather patterns (Li and others, 2008).

Precipitation also can be estimated from satellites, and with increasing resolution and accuracy. Satellite precipitation

Finding 9: *In Situ* Precipitation Measurement. There is an opportunity to form a robust precipitation measurement network in the U.S. with existing gages operated by numerous Federal, State, and local agencies, research organizations, and private citizens. However, lack of coordination, protocol, and communication among the organizations impedes formation of such a network. Because of this lack of coordination among precipitation gage operators, there has been no broad analysis of precipitation measurement needs.

estimates are less accurate than gage and radar measurements, but satellite estimates can be provided in near-real time (an advantage over many gages), and everywhere, including over the oceans and in mountainous regions (an advantage over both gages and radar). Numerous satellite precipitation products are available including STAR (National Oceanic and Atmospheric Administration, 2011g; CMORPH (National Oceanic and Atmospheric Administration, 2011h); TMPA-RT, which is produced byTRMM ((National Aeronautic and Space Administration, 2011a); and PERSIANN (CHRS-PERSIANN-CCS, 2011). As with radar, these estimates require some calibration and bias correction, especially for hydrologic applications (Behrangi and others, 2011; Tang and others, 2010). As with *in situ* gages, satellites require maintenance and eventual replacement.

Finding 10: Remotely-Sensed Precipitation Measurements. Radar and satellite precipitation measurement capabilities have provided precipitation estimates over areas not covered by ground-based gages. These estimates, however, rely on gage data for calibration and bias correction.

The NRCS has been collecting snow and climate data and producing water supply forecasts in 12 western States and Alaska for 76 years (U.S. Department of Agriculture, 2011b). As part of this collection system, many of the automated SNOTEL (U.S. Department of Agriculture, 2011e) sites, which transmit data in near-real time, have been in operation since the middle 1970s and presently the network consists of 813 stations. NRCS and its many partners also collect manual snow course data each month during the snow season at up to 900 sites throughout the Western U.S. and Alaska. NRCS has proposed to coordinate and provide technical leadership for collection and dissemination of snow information over a greater area of the U.S. (National Resources Conservation Service, 2011), which could enhance products from NOAA's Snow Data Assimilation System, described below.

NOAA's National Operational Hydrologic Remote Sensing Center NOHRSC (National Oceanic and Atmospheric Administration, 2011i) integrates airborne and satellite snow observations from all available electronic sources for the coterminous U.S. These data are used along with data from SNOTEL (U.S. Department of Agriculture, 2011b) to generate estimates of snowpack characteristics generated by a physically-based snow model to generate the National Snow Analyses (NSA) (U.S. Department of Agriculture, 2011c) on a daily basis for the coterminous U.S., as shown in figure 10. Ground-based and remotely-sensed snow observations are assimilated daily into the simulated snow-model state variables including snow water equivalent, snow depth, surface and profile snowpack temperatures, snowmelt, surface and blowing snow sublimation, snow-surface energy exchanges.

The SNOw Data Assimilation System (SNODAS) is a modeling and data assimilation system developed by NOHRSC to provide the best possible estimates of snow cover and associated parameters to support hydrologic modeling and analysis. The aim of SNODAS is to provide a physically consistent framework to integrate snow data from satellite, airborne platforms, and ground stations with model estimates of snow cover. SNODAS is an important resource but it currently lacks a reanalysis of its data. Without this, a climatology cannot be developed, so there is no way to put the current SNODAS measurements into a historical context. Development of such a climatology would be an important step for the product.

Finding 11: Snowpack Monitoring. The Natural Resources Conservation Service's SNOTEL (SNOwpack TELemetry) network operates in 12 western States and Alaska. NRCS has proposed to coordinate and provide technical leadership for collection and dissemination of snow information over a greater area of the U.S., which could enhance products from NOAA's Snow Data Assimilation System.

Almost all of the world's freshwater is located in glaciers and icecaps, and concerns about the effect of glacier loss on water supplies (although not necessarily in the U.S.), sea level [potentially tens of meters of sea-level rise (U.S. Geological Survey, 2000)], and ocean circulation support continued monitoring and research. Glaciers in the U.S. are monitored by the National Park Service (Denali National Park, North Cascades

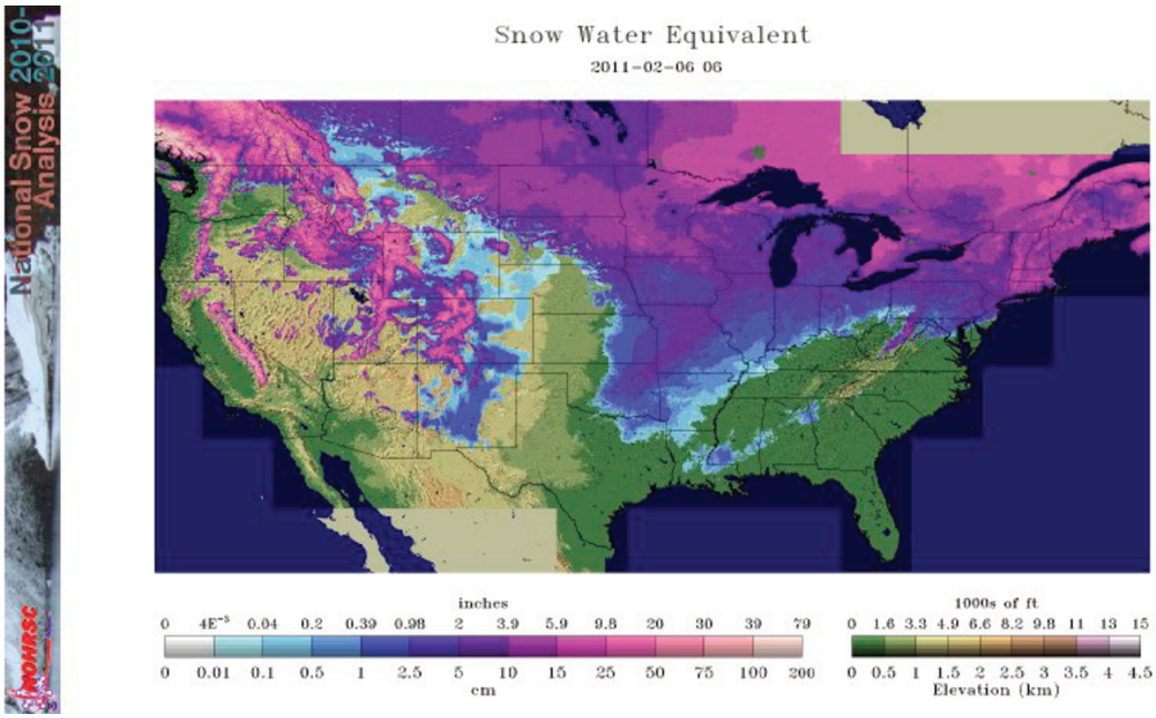


Figure 10. Example map of snow-water equivalent for the coterminus U.S. during February 2011 (U.S. Department of Agriculture, 2011a). Animated maps can be produced to display daily variations in snow depth, snowpack temperatures, sublimation, and other statistics.

National Park, Glacier National Park, Mount Ranier National Park, and elsewhere; for example, North Cascades National Park Complex at *http://www.nps.gov/noca/naturescience/glacial-mass-balance1.htm*), the USGS (three benchmark glaciers; for example, USGS Benchmark Glaciers at *http://ak.water.usgs.gov/glaciology/*), and academic researchers. The World Glacier Monitoring Service (*http://www.geo.uzh.ch/microsite/wgms/*) compiles information from global glacier monitoring, and the Service provides guidelines and standards for glacier monitoring. Much glacier monitoring can be conducted from satellites (for example, Landsat, ASTER, and SPOT), but ground-based measurements are required for calibration and testing of remote-sensing methods (for example, Paul and others, 2007).

Finding 12: Glacier Monitoring. Glacier monitoring is important, given the potentially large effect glacier meltwater could have on sea level and ocean circulation. A combination of ground-based and satellite monitoring is warranted. As in many monitoring efforts, there is some lack of coordination among existing monitoring activities.

Grinnell Glacier (at upper right in photograph) in Glacier National Park, Montana.

Water Quality and Ecosystem Condition

Water-quality data include physical characteristics such as temperature and suspended solids; chemical characteristics such as pH, alkalinity, minerals, metals, nutrients (nitrogen and phosphorus), organics (including naturally occurring substances; pesticides, pharmaceuticals, and other anthropogenic compounds; and byproducts or degradation products such as nitrosamines or other disinfection byproducts); and microbial characteristics such as viruses, bacteria, protozoa, and algae. Many of these parameters are interrelated and have direct public health implications (Noyes and others, 2009).

Water-quality data are measured in a variety of media, including surface waters, groundwater, precipitation, sediment, and plant and animal tissue. Hydrologic conditions under which data were collected are a key part of the data set. Without this information, water-quality data are less valuable and more difficult to interpret.

Climate influences water quality directly through changes in temperature and precipitation patterns. Changes in temperature also affect microbial and chemical reaction rates including those controlling degradation of contaminants, solubility, and pathogen survival and die-off. Temperature affects evaporation rates and consequently salinity (salt content), particularly in lakes. Intensified precipitation can accelerate runoff and sediment erosion and deposition rates, as well as atmospheric deposition into water bodies. Drought and heavy precipitation events have been correlated with increased incidence of waterborne disease (Nichols and others, 2009). Changes in land and water management will affect contaminant inputs to freshwater, both positively and negatively. The effects of these types of changes can be immediate and profound (Scanlon and others, 2007), with climate change potentially adding to the effects of these other stressors.

Some types of water-quality data can be collected using *in situ* sensors to provide real-time data. Remote sensing and satellite imagery can provide spatially-coarse information on algal blooms, turbidity, and temperature. This technology is most appropriate for large water bodies. Remotely-sensed information on land cover is valuable for evaluating sources of contaminant loadings for relating measured loads to management actions. Perhaps most commonly, water-quality data are obtained from laboratory analyses of water samples collected at specific locations (streams, groundwater, wastewater, drinking water systems, outfalls, intakes, etc.). The specific types of water-quality data that are collected and the frequency of sampling depend on resource availability, sampling protocols, and regulatory requirements.

Water-quality data are collected by Federal, State, Tribal, and local agencies, interstate commissions, the academic community, and citizen volunteers for a variety of purposes. There have been numerous reports in recent years indicating that this level of monitoring is insufficient and/or not well enough coordinated to provide comprehensive information about U.S. water resources (for example, U.S. Government Accountability Office, 2004; H. John Heinz Center for Science, Economics, and the Environment, 2002). This is due, at least in part, to an inability to access and integrate the data that are collected by the various organizations engaged in water-quality monitoring.

The USGS collects and analyzes chemical, physical, and biological characteristics of water, sediment, and tissue samples from across the Nation and compiles the data into the NWIS database (U.S. Geological Survey, 2011b). The USGS National Stream Quality Accounting Network (NASQAN) Network (U.S. Geological Survey, 2011g) consists of 21 sites on major drainages to the Mississippi River, as well as the Mississippi River itself (fig. 11). The network originally supported about 618 sites in the mid-1970s (Alexander and others, 1997). This decline in the number of sites reflects the challenges of maintaining a robust monitoring network with level funding.) The USGS National Water-quality Assessment Program (NAWQA) collects samples at 113 sites, some of which are sampled annually, some every two years, and some every 4 years (fig. 12). An additional 58 wadeable streams are sampled for water chemistry and ecological conditions. Additionally, about 1,300 surface-water and groundwater sites are instrumented to continuously record physical and chemical characteristics of the water including pH, specific conductance, temperature, dissolved oxygen, and percent dissolved-oxygen saturation (U.S. Geological Survey, 2011a). Investments in sensor technology would greatly enhance the Nation's water-quality monitoring capabilities.

The USEPA conducts sampling designed to statistically answer questions about the overall quality of the Nation's waters. The Wadeable Streams Assessment (U.S. Environmental Protection Agency, 2006) sampled 1,392 randomly selected sites. Macroinvertebrates were used to assess the condition of the streams relative to reference (unimpacted) streams. Following a similar design as the Wadeable Streams Assessment, the National Lakes Assessment sampled 1,028 lakes in the U.S. in 2007 in order to obtain a statistical measure of the health of the Nation's lakes (U.S. Environmental Protection Agency, 2010a). These assessments are designed to be repeated at regular intervals.

States conduct both statistical surveys and targeted monitoring under USEPA guidance. States are required to report to USEPA every two years on the condition of their surface waters, as required under sections 303(d) and 305(b) of the Clean Water Act. The reports generally identify the water bodies that are impaired for the designated uses and the causes of impairment. USEPA maintains a database of the State reports (U.S. Environmental Protection Agency, 2011c).

A National Water-Quality Monitoring Network design was developed by a large group of participants through the National Water-Quality Monitoring Council (2008). The network design is consistent with the National Ocean Council's Strategic Action Plan (2011) priority objectives on Water Quality and Sustainable Practices on Land (objective 7) and Ocean, Coastal, and Great Lakes Observations, Mapping, and Infrastructure (objective 9). If implemented, the network will provide integrated and coordinated data on the Nation's water

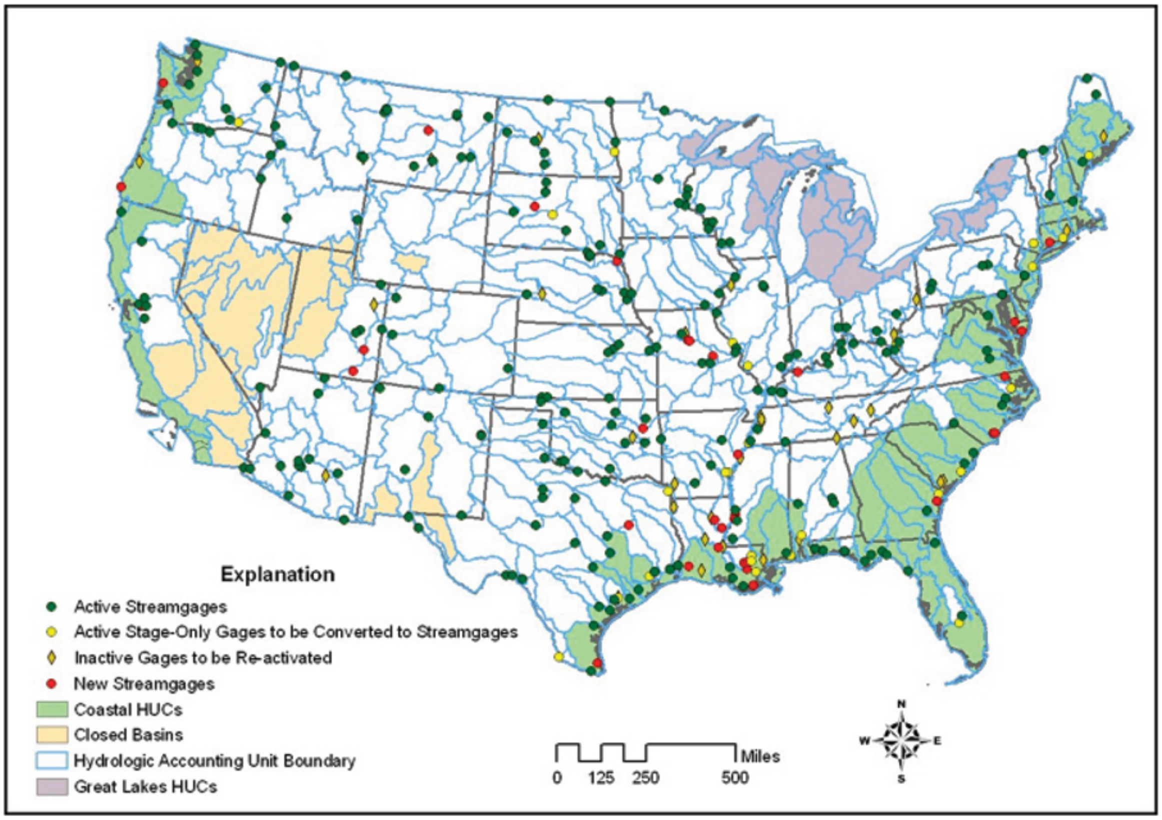


Figure 11. Map of the conterminous United States, showing Hydrologic Accounting Unit boundaries, closed basins, coastal basins, Great Lakes basins, and proposed sites for the National Water-Quality Monitoring Network (National Water-Quality Monitoring Council, 2008).

quality from the uplands to the coasts. The design is based on five objectives to answer important management questions (National Water-Quality Monitoring Council, 2008). The network also is designed to link with the Integrated Ocean Observing System; is based on a multi-disciplinary approach that integrates water resources from the uplands to the coast, integrating physical, chemical, and biological measures; and stresses the importance of metadata, comparable methods, quality assurance, and data archival. The rivers component of the network (fig. 12) includes 258 sites representing 90 percent or more of the flow from each Hydrologic Unit Code sixth-level (HUC-6) watershed (U.S. Geological Survey, 2011h) in the country, 72 sites at locations draining directly to key estuaries, and 56 sites to document flows and loads to the Great Lakes. Currently, 5 stations of the network are funded by the USGS as a sub-network of the National Stream Quality Accounting Network (U.S. Geological Survey, 2011i).

Finding 13: Water-Quality Networks. Extensive water-quality monitoring is conducted in the U.S., and various networks have evolved to meet user needs. Integration of data from the various networks could offer benefits, if data were comparable and well integrated. The proposed National Monitoring Network offers a sound basis for understanding fluxes of key contaminants from major basins across the Nation.

Water-quality issues associated with climate change are likely to have multiple public health impacts due to shifts in the microbial ecology of freshwater and coastal systems, new and different pathogens and chemical contaminants, and an increase in algal blooms. Heavy precipitation events have been statistically linked to an increased incidence of waterborne disease outbreaks in the United States (Interagency Working Group on Climate Change and Health, 2010a; Curriero and others, 2001). The anticipated increase in the risk for waterborne disease with climate change will require improved surveillance systems and coordination of prevention efforts at local, State, and national levels. While the types of data systems needed to monitor the incidence and prevalence of waterborne disease differ from other monitoring networks, it is important to integrate geospatial water resource data with public health data. The Centers for Disease Control and Prevention's (CDC) National Environmental Public Health Tracking Network (*http://ephtracking.cdc.gov/showAbout.action*) could

Finding 14: Waterborne Pathogens. Prevalence of waterborne pathogens, including harmful algal blooms, likely will change in response to rising temperatures, as well as to alterations in flow characteristics and contaminant loadings. Systems for tracking these changes are not well developed, nor are they well integrated with geospatial, water-quality, and public health information.

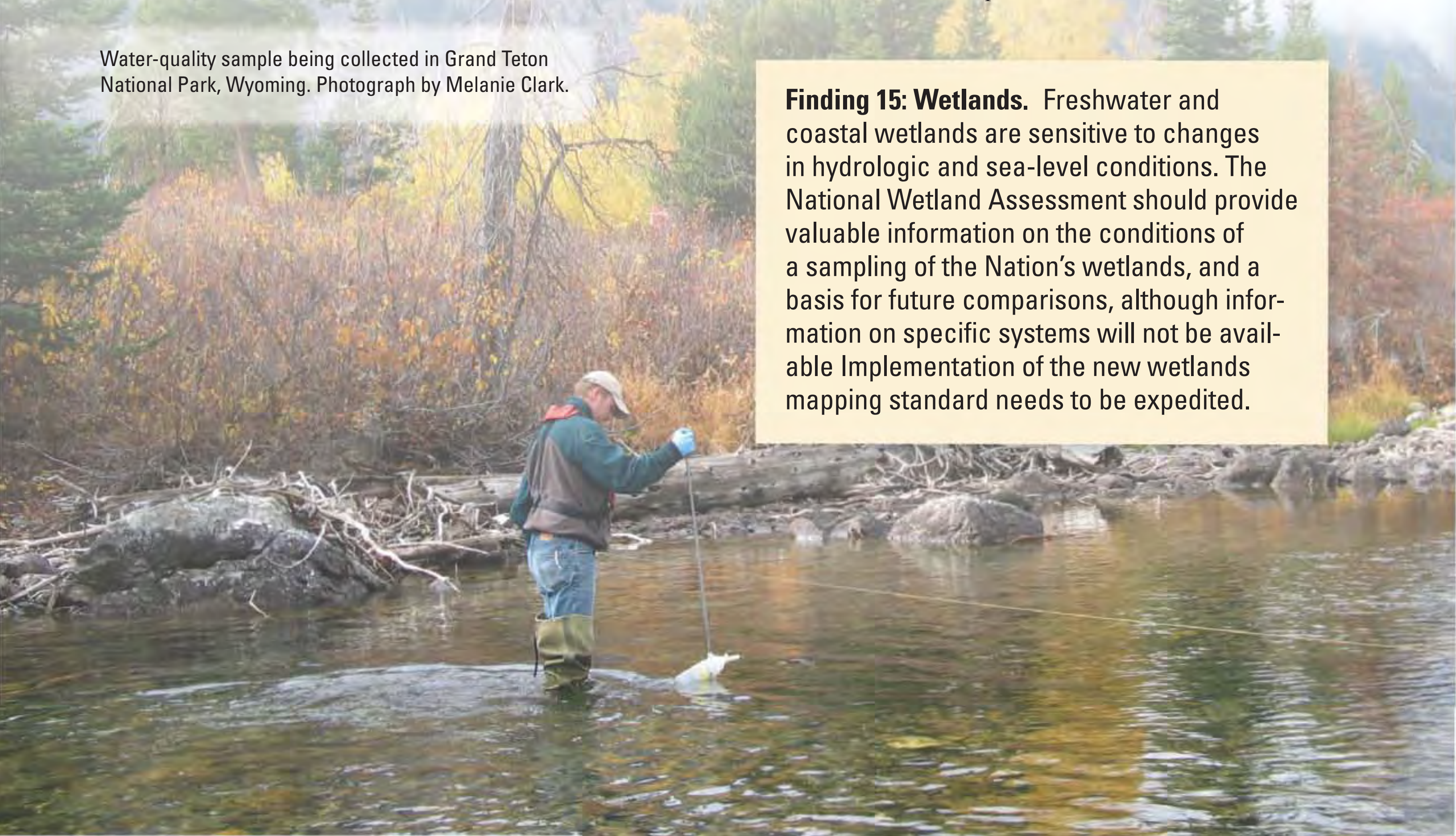
be a potentially valuable source of information for tracking waterborne disease data and for protecting human health.

Key issues include:

- Endemic disease and outbreaks associated with exposure to waterborne pathogens;
- Surveillance of diseases associated with waterborne contaminant exposures (chemicals and their byproducts and metabolites, toxins released by algae and cyanobacteria, etc); and
- Surveillance of developmental health effects relevant to waterborne contaminants (microbial and chemical).

Wetlands are sensitive to changes in hydrologic conditions. Small changes in groundwater levels can determine whether a wetland thrives or disappears. The effect of climate change on wetlands will depend on the location of the wetland within the hydrologic landscape, and the magnitude of temperature and precipitation changes (Winter, 2007). Changing sea level already is impacting coastal wetlands, causing wetland retreat in many locations (for example, Williams and others, 1999; Lanthrop and Love, 2007). USEPA has begun a National Wetland Assessment (*http://water.epa.gov/type/wetlands/assessment/survey/index.cfm#about*) designed to provide regional and national estimates of wetland ecological integrity. The assessment will use a probability-based design, similar to that used for the Wadeable Streams Assessment, to produce statistically-valid estimates of conditions for various wetland types.

The Wetlands Mapping Standard was developed and formally endorsed by the Federal Geographic Data Committee in response to the need for a higher degree of wetlands data. However, implementation of the standard by States is not yet fully realized. Use of the standard will help provide a more complete and accurate picture of wetland resources in the United States. Wetlands are inextricably tied to water levels and changes in climatic conditions affecting water availability will greatly influence the nature and function of specific wetlands, including the type of plant and animal species within them. In developing this mapping standard, an effort was made to identify and accommodate technology and map-scale enhancements that will ensure long-term use of the standard and minimize the need for revisions and updates.



Water-quality sample being collected in Grand Teton National Park, Wyoming. Photograph by Melanie Clark.

Finding 15: Wetlands. Freshwater and coastal wetlands are sensitive to changes in hydrologic and sea-level conditions. The National Wetland Assessment should provide valuable information on the conditions of a sampling of the Nation's wetlands, and a basis for future comparisons, although information on specific systems will not be available Implementation of the new wetlands mapping standard needs to be expedited.

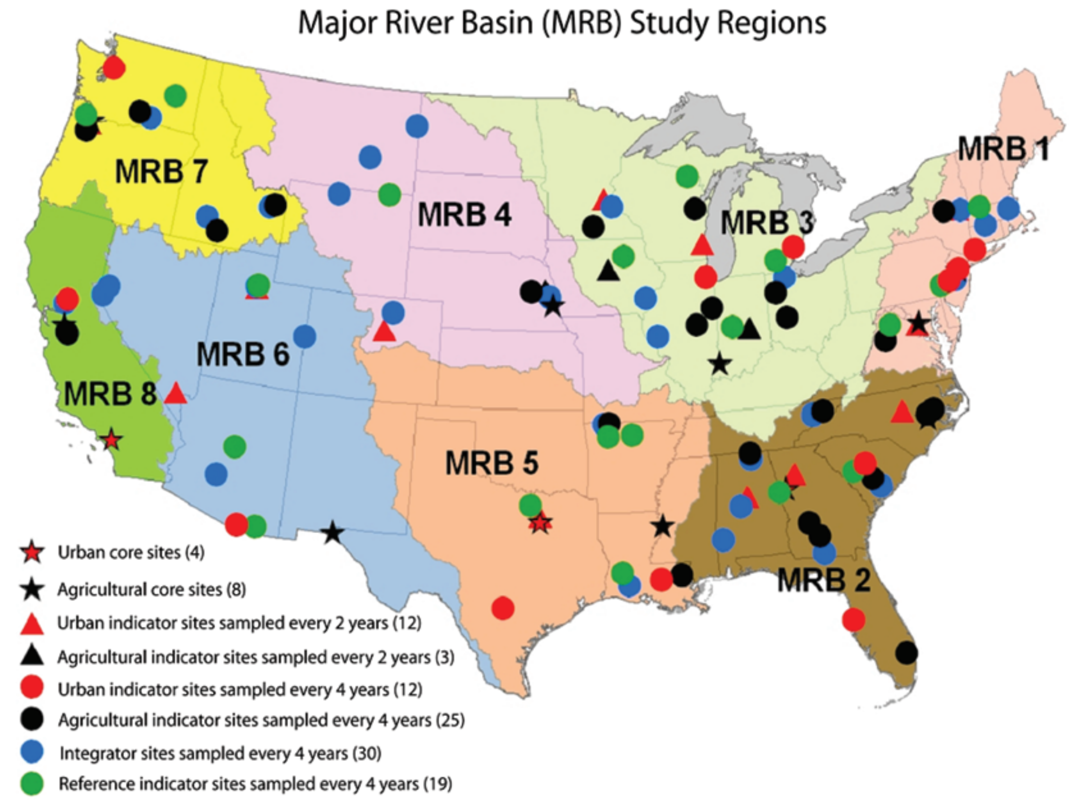


Figure 12. U.S. Geological Survey National Water-quality Assessment Program water-quality trend sites (*http://water.usgs.gov/nawqa/studies/mrb/images/mrb_sites_lg.png*).

Water Withdrawals and Consumptive Use

Water withdrawal data generally are collected by States, water management districts, and utilities. In many cases, withdrawals are estimated from proxies, rather than directly. Information is collected and reported differently from State to State, and almost no data are available on consumptive use (as opposed to total withdrawals of water) (National Research Council, 2002).

The USGS works in cooperation with local, State, and Federal environmental agencies to compile, and disseminate water withdrawal information through the National Water-Use Information Program (NWUIP) (U.S. Geological Survey, 2009a) at five-year intervals. Information on consumptive use has not been reported since 1995. Data are searchable through the USGS National Atlas (U.S. Geological Survey, 2011j). The USDA conducts an agricultural census (U.S. Department of Agriculture, 2011d) and also conducts a farm and ranch survey (FRS) to provide a snapshot of agricultural water use (U.S. Department of Agriculture, 2008). These data are compiled and summarized on the basis of political boundaries (States, counties) and do not necessarily reflect watershed characteristics.

Numerous reports have documented the close link between energy production and water use (see Mielke and others, 2010, for a recent review). Water is required for energy extraction, transportation, processing, and production. Energy is used to withdraw, treat, and transport water. The Department of Energy collects some water withdrawal data through the Energy Information Administration (U.S. Energy Information Administration, 2011); a recent GAO (U.S. Government Accountability Office, 2009) report has recommended some enhancements to that program. Changes in the Nation's energy portfolio (increased use of biofuels; new hydrocarbon energy extraction methods) and increased use of carbon sequestration, already are having an effect on water resources. Monitoring networks do not exist to address these issues (U.S. Government Accountability Office, 2009).

The national Water Census (U.S. Geological Survey, 2007) and the Department of Interior's (DOI) WaterSMART Program (U.S. Department of the Interior, 2011) are important steps towards providing a comprehensive perspective on water resources. The Water Census, which is modeled in large part on 2002 recommendations from the National Research Council (National Research Council, 2002) is designed to describe the changing availability, quality, location, and uses of water resources. This key information needs to be readily available to water managers and the public.

The Water Census will be organized on a watershed basis and contain:

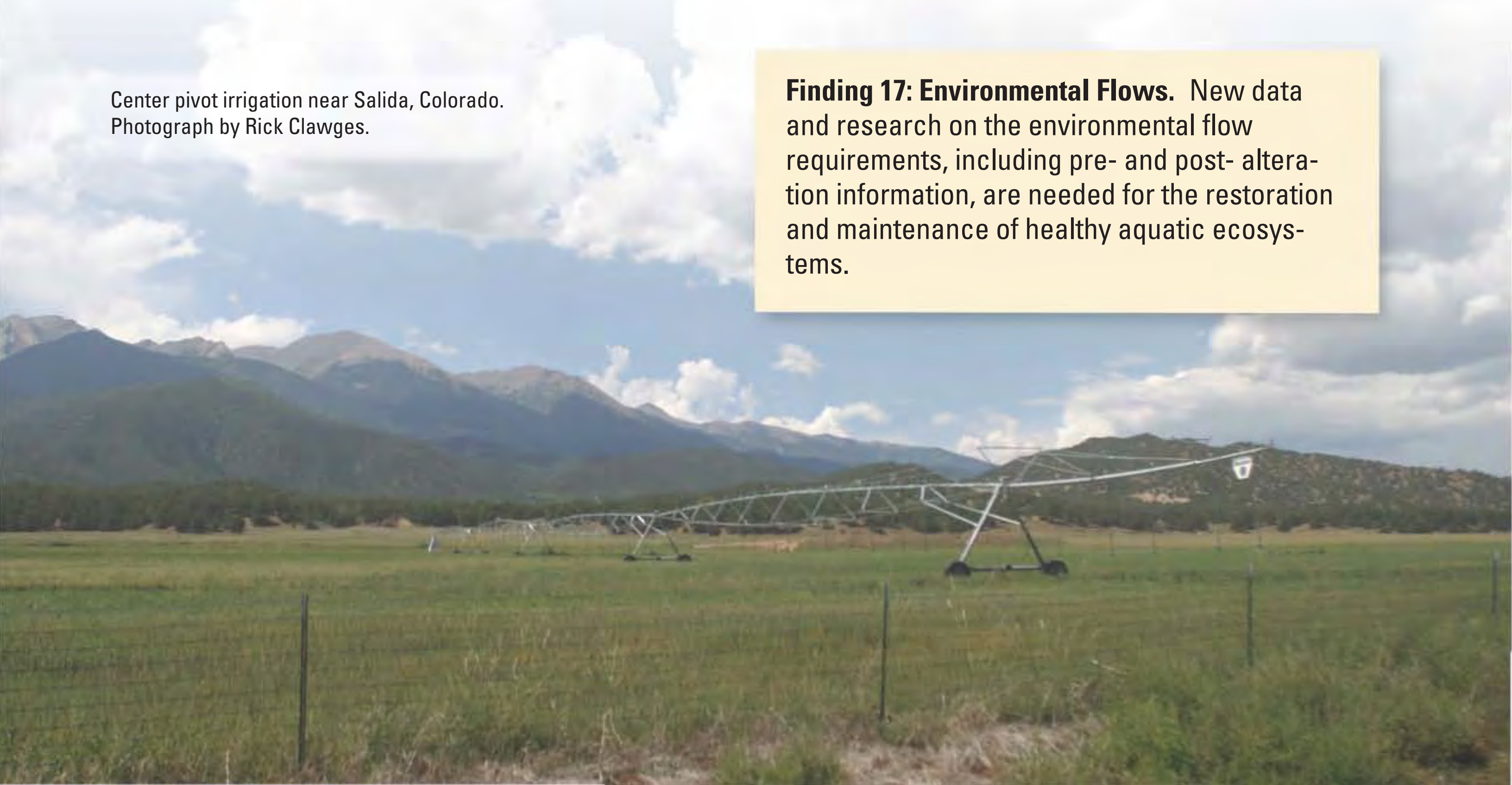
- Water use information: withdrawals, return flows, and consumptive use for all water use sectors with special data collection efforts designed to track changing water use patterns relevant to public water systems, agriculture, energy, industry, and non-potable demands;
- Water quantity and availability information including analysis of changes in storage (groundwater) and flow (rivers);
- Analysis of changes in water quality that are critical to its use (temperature, sediment, nutrients, pathogens, salinity, waterborne contaminants) and;
- Identification of alternative water sources that may become available through technological advances including reuse, green infrastructure, conservation, desalination, aquifer storage and recovery and evolving energy production and industrial water use practices.

As a part of the Water Census design, there are plans to provide grants to States to help improve the quality of the Nation's withdrawal and consumptive use data, and to develop common methods for collecting and reporting the data.

The concept of water use is expanding to include environmental flows, or the flows required to maintain a functioning and healthy ecosystem, such that rivers and streams are now considered important 'users' of water (Naiman and others, 2002; Postel and Richter, 2003). The concept embodies the provision of suitable habitat for living aquatic resources—both plants and animals. Alterations of flow from natural conditions are known to elicit an ecological response (Poff and Zimmerman, 2010). Flow alterations are defined as any change from natural conditions in the magnitude, frequency, duration, timing, and rate-of-change of flows.

Finding 16: Withdrawals and Consumptive Use of Water. Water withdrawal and consumptive use data, particularly as related to the Nation's energy portfolio, are inadequate for making long-term decisions about water availability in the U.S.

The management of freshwater systems to meet both human and ecological needs remains a major challenge (Arthington and others, 2006; Poff and Zimmerman, 2010). For example, in the Pacific Northwest, projects to improve habitat for salmon are "moving forward with little or no knowledge of specific linkages between restoration actions and the responses of target species." (National Oceanic and Atmospheric Administration, 2011j). Stream-by-stream and species-by-species analysis of environmental flow needs is not practical. Even when environmental flow needs are well defined, the challenge of maintaining a balance between environmental flows and human needs for water supply, waste assimilation, navigation, power generation, and other uses can be difficult and contentious. New data and research on the environmental flow requirements, including pre- and post- alteration information, are needed for the restoration and maintenance of healthy aquatic ecosystems.



Center pivot irrigation near Salida, Colorado. Photograph by Rick Clawges.

Finding 17: Environmental Flows. New data and research on the environmental flow requirements, including pre- and post- alteration information, are needed for the restoration and maintenance of healthy aquatic ecosystems.

Review Element 3: Improve Data Management to Increase Efficiency of Data Acquisition and Reporting

Review Element from Section 9506:

> *"to establish data management and communication protocols and standards to increase the quality and efficiency by which each Federal agency acquires and reports relevant data…"*

Robust tools for managing data are essential for effective decision-making. Data management practices have advanced over the past decade due to the evolution of information technology, improved communication tools, and improved decision support tools.

Currently there are dozens of data management approaches (see Appendix B for some important examples) that are in use and a host of databases that house various types of water data and information The interoperability of these systems varies and there are ongoing efforts to improve coordination. Obstacles to data sharing include differing geospatial reference systems, lack of common definitions for the same measure, and inadequate metadata. Most data are accessible via the internet and digital copies of the data can be retrieved.

A major challenge facing producers of water information is ensuring that data are accessible, quality-controlled, and available in formats that facilitate their use by stakeholders. Over the past decade, a number of Federal agencies and other institutions have expanded their water databases, and developed a range of information management tools to help ensure compatibility and interoperability of disparate data sets so they can be applied to a variety of purposes. The USEPA maintains a water-quality data warehouse called STORET (U.S. Environmental Protection Agency, 2011d) that catalogues water-quality data by location and properties (physical, chemical, biological and habitat). STORET is updated regularly and its data record ranges from the 1970s to the present. Data in STORET tend to be focused on water or wastewater treatment facilities or watersheds of concern. Because the data are derived from different entities, all inputs must document a standardized set of metadata that include: the sampling and analytical methods used; in appropriate situations, the laboratory used to analyze the samples; and the quality control checks used when sampling, handling the samples, and analyzing the data.

While NWIS and STORET are designed for different purposes, the systems are developing collaborative websites to provide data to users in a common format. These systems have developed standardized metadata, compatible search parameters and common vocabulary that will allow for greater functionality of available data to be used for climate change analysis. This approach will allow data users to access data from both databases. Efforts are underway to expand this effort to include other data systems, thus allowing for greater consistency across a wider range of water body types.

Finding 18: Interoperable Data Systems. Ready access to the full range of hydroclimatic data collected by government agencies and other interests is inadequate. Data are collected using a range of protocols, which are not always documented, and are archived in a variety of ways, from modern relational databases to paper copies in files. There is much to be gained from use of consistent documentation standards and improvements in interoperability of data systems.

A variety of institutions are exploring options for enhancing interoperability. One effort that has seen some initial promising results is the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), Hydrologic Information System (HIS) project, funded by the National Science Foundation (NSF) and led by a multi-institutional research team. This group has been studying how to synthesize the water data by means of a services-oriented architecture. A large scale prototype water information network has been constructed that presently provides access to over 50 water-data services including significant proportions of the water data holdings of the USGS and USEPA, information from NWS, National Climate Data Center (NCDC), USDA-NRCS and other agencies at the Federal and State level, as well as water data from a dozen universities (see *http://hydrodesktop.codeplex.com/*). HIS is used by multiple agencies in the State of Texas to share data operationally and is being promoted by the Niagara Peninsula Conservation Authority to link information across cities along the Great Lakes. CUAHSI has defined a language called WaterML (Water Markup Language) for conveying time series of water observations data through the internet. The USGS and some other water agencies now publish some of their observations data in WaterML. USEPA has developed a web services language called WQX (Water Quality Exchange) that conveys groups of water-quality observations, and CUAHSI has developed a translator that converts WQX into WaterML so that time series of physical hydrology and water-quality data can be acquired in a consistent way.

The Open Geospatial Consortium (OGC) (*http://www.opengeospatial.org/*) is an international organization, representing about 400 companies and agencies, which has developed the most widely used standards for sharing geospatial data through the internet. In 2008, CUAHSI proposed to the OGC that there should be established a Hydrology Domain Working Group to harmonize WaterML with OGC standards, and later the OGC and the World Meteorological Organization expanded this mission to included joint development of data standards for hydrology, climatology, oceanography and meteorology.

The CUAHSI Hydrologic Information System project has concluded that the best approach to enhance internet-based water data sharing in the United States is to adapt existing OGC data standards. Climate and weather grid information can similarly be searched and accessed by being indexed in a consistent way with water resources time series. The ACWI/FGDC Subcommittee on Spatial Water Data supports this approach to developing water data services in the United States. Leadership at the Federal level will be needed to develop strategies to enhance water data sharing across all levels of government, among water disciplines, and between water science and water management in the United States and with bordering nations.

The U.S. Integrated Ocean Observing System (IOOS®) is a national observing system that integrates, coordinates and enhances efforts to deliver coastal and near-coastal information to decision-makers to improve safety, enhance our economy, and protect our environment. The integration of information facilitated by open source standards and protocols, such as the Open Geospatial Consortium Sensor Observation Service, and data formats that enable more efficient, routine, and effective use of data is key to building IOOS®. IOOS® and the National Water-Quality Monitoring Network for U.S. coastal waters and their tributaries have been coordinating to bridge water-quality data collected in rivers and watersheds with data from the estuaries to coastal waters and the Great Lakes in order to facilitate seamless use of the data.

A reliable system to monitor and report the occurrence and prevalence of waterborne disease would aid in understanding the role of climate and other driving factors in the distribution of those diseases. Officials at the Centers for Disease Control and Prevention (CDC) have recognized the need for such a system and it is important that this effort is coordinated with development of data systems focused on changes in the natural environment.

In general, hydroclimatic data are insufficiently integrated (or integratable by the user community) to support important management decisions. For example, most water-quality data are not integrated with water quantity data. Likewise, groundwater and streamflow data generally are not integrated, thereby limiting, for example, understanding the effects of groundwater pumping on streamflow. Hydroclimatic data are not connected to issues of social relevance. For example, the capacity does not exist to link information about vulnerable human populations with data about implications of changes in the hydroclimatic cycle (that is, frequency and magnitude of floods and droughts).

Accelerated progress is needed on:

- Multi-agency cooperation to deliver information seamlessly;
- National integration of observational data and metadata;
- Adoption of common operational standards, quality assurance procedures, and data exchange formats;
- Data interoperability;
- Coordination of all types of hydroclimatic monitoring; and
- Linkage of hydroclimatic data to issues of social relevance.

These efforts need to be coordinated with hydrogeological and biogeochemical modeling of freshwater resources and ensure the right types of data are being collected at the right locations and frequency.

Finding 19: Data and Decision-Making. In general, hydroclimatic data are insufficiently integrated (or readily integratable by the user community) to support important management decisions, and hydroclimatic data are inadequately connected to information on issues of social relevance.

Review Element 4: Options for Establishment of a Data Portal

Review Element from Section 9506:

"to consider options for the establishment of a data portal to enhance access to water resource data…"

There are a number of ongoing efforts within single agencies or jointly among agencies to develop data portals that allow for data integration. Easy internet access to hydroclimatic information and data is a high priority for all stakeholders. As an example, the USGCRP has proposed establishing an "Interagency Climate Information Portal" to provide web-based access to critical climate information, including climate data, models, resources and tools, for decision makers and the public.

As data are coordinated, it is clear that the quantity of data available for a given watershed depends on basin location relative to issues that drive monitoring and resources available for consistent data collection. There are opportunities for integrating geospatial analyses with sensor data through a portal.

An important challenge is to ensure that a data portal is designed to maximize access to and utility of the data. As a result, decision-makers and other end-users need to play an integral role in portal development and testing, and the entry point needs to be self-explanatory and allow for data to be accessed by a range of users with different levels of experience and expertise. Language, semantics, data definitions, and criteria need to be developed collaboratively with inputs from all stakeholders (decision-makers, modelers, information technology, database developers, the user community, etc.) so that information is accessible and useful to the appropriate audiences and guidance is provided on best management practices.

Portal design needs to consider how to best link information to its original source to enable users to query the data in different ways and access more details as necessary. The portal design needs to be flexible enough to adapt to changing information technology. Robust quality standards are needed to ensure the credibility and reliability of the portal.

Finding 20: New Data Portals. A new effort by the U.S. Global Change Research Program, using existing agency resources, has been initiated to build an interagency data portal, and this portal also may provide access to hydroclimatic data. The initial phase of this process, conducted with strong coordination among Federal and non-Federal partners, is expected to focus on data generated in support of the National Climate Assessment. The portal also is expected to provide guidance on appropriate use of data and on the use of probabilistic information. Other efforts to better organize data, such as the Integrated Water Resources Sciences and Services activity, also should contribute to enhanced data access.

Review Element 5: Adequacy of Hydrologic and Other Models

Review Element from Section 9506:

> *"to facilitate the development of hydrologic and other models to integrate data that reflects groundwater and surface water interactions…"*

Successful management of our Nation's water resources requires an integrated approach. Models provide decision-makers with tools that can be used to simulate and visualize water quantity and quality under the range of climatic, hydrologic, and environmental conditions that reflect the current and future state of water resources. Models can be used to help explore potential future climate scenarios at relevant scales for:

- Prediction of basin response to extreme rainfall and snowmelt through application of precipitation-runoff models to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and groundwater recharge resulting from climate change;
- Evaluation of the effect of predicted climate scenarios on streamflow, sediment delivery, and water balance in watersheds;
- Evaluation of interactions between streamflow and groundwater levels; and
- Planning and design of urban drainage systems, flood control structures, water-supply storage, and other water infrastructure.

Models can generally be classified as statistical or process-based, although process-based models can be applied statistically. Process-based models are those based on underlying physical, biogeochemical, and ecological processes.

As previously noted, statistical hydrologic models have been based on the assumption that past distributions of precipitation and basin response are a good indicator of future distributions. It generally is recognized now, however, that this assumption of stationarity is not valid (Milly and others, 2008), and likely never was valid. As a result, statistical understanding and models of future precipitation and streamflow characteristics needs to be improved. Models describing frequency of large precipitation events and the magnitude and intensity of those events also need to be improved. Likewise, statistical models of flood and drought recurrence and magnitude must be modernized in order to effectively plan for future conditions.

The capacity of process-based models is continuing to advance improvements in computing power, visualization capabilities, incorporation of remotely-sensed data, and research leading to better understanding of controlling processes. Integration of processes (for example, groundwater and surface water; hydrology and water chemistry) and feedbacks among processes (for example, hydraulic conditions and channel morphology; land-climate interactions) is a challenge, although progress is being made (Markstrom and others, 2008).

While there are significant efforts underway to develop ecosystem models and evaluate the services that ecosystems provide, there is a need to better integrate work on ecological processes with water resources data, models, and tools. Models for predicting how aquatic habitats respond to changing hydrology, water quality, and climate are needed. As aquatic habitats change, plant and animal communities will also adapt to changes in flow and water quality and a better understanding of these interrelationships is needed to evaluate the potential outcomes of climate mitigation and adaptation

Finding 21: Hydroclimatic Statistics and a Changing Climate. Statistical models of hydroclimatic events that are based on the assumption that future conditions will have the same statistical properties as past conditions are not valid. Improved understanding of the statistical characteristics of precipitation and streamflow are needed for effective planning and management under uncertainty.

approaches. As a result, it is difficult to forecast the full range of effects of management actions and/or climate change on the entire resource.

Regional climate models or down-scaled general circulation models/global climate models (GCMs) also are evolving and helping to provide insight on possible future climate scenarios. It is fairly clear, however, that current down-scaled GCM's do a poor job in hindcasting past precipitation and hydrologic conditions when climate is known (for example, Stephens, and others, 2010; Bae and others, 2011), so confidence in future predictions of hydrology is weak. As a result, there is a need to (1) more rigorously test down-scaled GCM's for water-resources planning applications, (2) develop guidance for appropriate applications, (3) document uncertainty in results, and (4) understand the implication of new finer-scaled GCMs for hydrologic applications.

Community modeling is gaining increasing acceptance as an alternative to proprietary or closed-source models. Community models serve the diverse needs of a particular modeling community and model capabilities are advanced through contributions from the entire community. As an example, NOAA's Community Hydrologic Prediction System (CHPS) (National Oceanic and Atmospheric Administration, 2011k) provides an open architecture that integrates observations, analytical tools, and models to produce water resource forecasts for a wide array of users (fig. 13). Approaches also are under development to downscale GCM outputs to regions and localities, to assist in resource decision-making (for example, Means and others, 2010). Some of the key objectives of current modeling efforts include understanding land surface-atmospheric interactions, complex terrain, and the role of decadal scale oscillations in ocean temperatures.

Finding 22: Integrated Modeling. Although there have been recent advances, current coupled groundwater-surface water models, and fully coupled hydrologic-water quality-ecosystem models are inadequate for forecasting the full range of effects of management actions and/or climate change on the entire resource.

The availability of reliable, up-to-date, readily accessible data is crucial to the effective development and use of models. Important data include:

- Components described in **Review Element 1**: Streamflow and surface-water data, groundwater-level data, soil moisture and evapotranspiration, precipitation (including rainfall, snowfall, snowpack characteristics, soil characteristics, and glacier mass), water quality, and water use information;
- Climatic measures such as temperature, wind speed, and direction;
- Physical measures of the landscape such as elevation, slope, and land use.
- Land cover;
- Societal demographics; and
- Paleoclimatic data for understanding the severity of past droughts and flood.

Finding 23: Global Climate Models. There is a need to develop and more rigorously test down-scaled Global Climate Models (GCM's) to provide more reliable projections of water-resources conditions for planning applications, and develop guidance for appropriate applications.

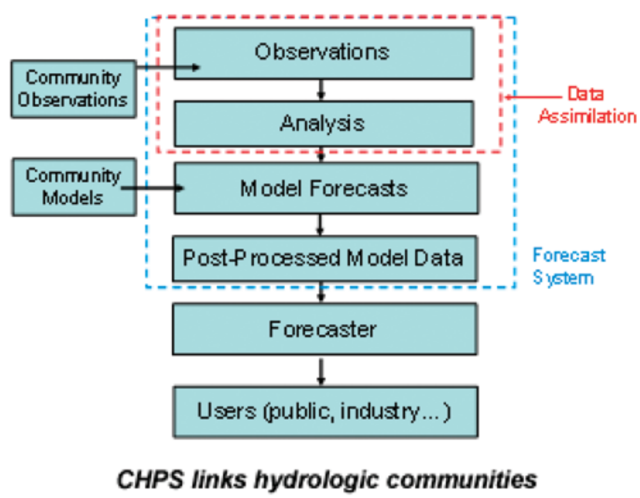


Figure 13. Architecture of the Community Hydrologic Prediction System (National Oceanic and Atmospheric Administration, 2011a).

Review Element 6: Apply Hydrologic Models to Water Resource Management Problems

Review Element from Section 9506:

> *"to apply the hydrologic and other models developed under paragraph (5) to water resource management problems identified by the panel, including the need to maintain or improve ecological resiliency at watershed and aquifer system scales…"*

Hydrologic models that predict watershed response to climate and land-use forcings have been in use for more than 30 years. Although models have improved in their ability to manage and display data, many of the underlying model algorithms remained unchanged from earlier versions. Hydraulic models, model movement of water through aquifers and streams, have improved capacity to predict water and solute movement in complex situations such as coupled river–floodplain systems, reservoirs, and estuaries. Water-quality models can perform reasonably adequate predictions of temperature, nutrient, dissolved-oxygen, and salinity in surface waters. Groundwater models also can predict salinity, temperature, and many dissolved constituents adequately. Prediction of other contaminants is more challenging, particularly contaminants that sorb and desorb to particulates. As suggested in **Review Element 5**, development and integration of models can be used to design follow-up field studies and also to inform policy decisions. Conversely, models can be used to optimize sampling programs and the development of monitoring networks.

Sustained, coordinated monitoring and ongoing analysis of data are needed to develop and implement effective structural and operational adjustments in response to observed system changes. A key barrier to applying climate change vulnerability assessment tools to ecosystems is the need to ensure that information and models that are used are appropriate for the scale of the decision (water body, watershed, regional, national). Adaptive management requires institutions to re-evaluate project and program performance and to revise decisions based on the most recent information, which requires a commitment to ongoing monitoring.

There are several efforts currently underway to assist in meeting these challenges, including the Water Utilities Climate Alliance (WUCA) and the Integrated Water Resources Science and Service (IWRSS). WUCA (*http://www.wucaonline.org/html/*) is a consortium of 10 large water utilities that was formed to provide leadership and collaboration on climate-change challenges facing the Nation's water managers. The IWRSS currently is a partnership of NOAA, the Corps of Engineers, and USGS, agencies with complementary operational missions in water science, observation, prediction and management (fig. 14).

The National Science and Technology Council's (NSTC) Subcommittee on Water Availability and Quality (SWAQ) is the one venue in which all Federal agencies with any responsibility (or interest) in water issues gather regularly to exchange information. The SWAQ advises and assists the NSTC on policies, procedures, plans, issues, scientific developments, and research needs related to the availability and quality of water resources of the United States within the context of the

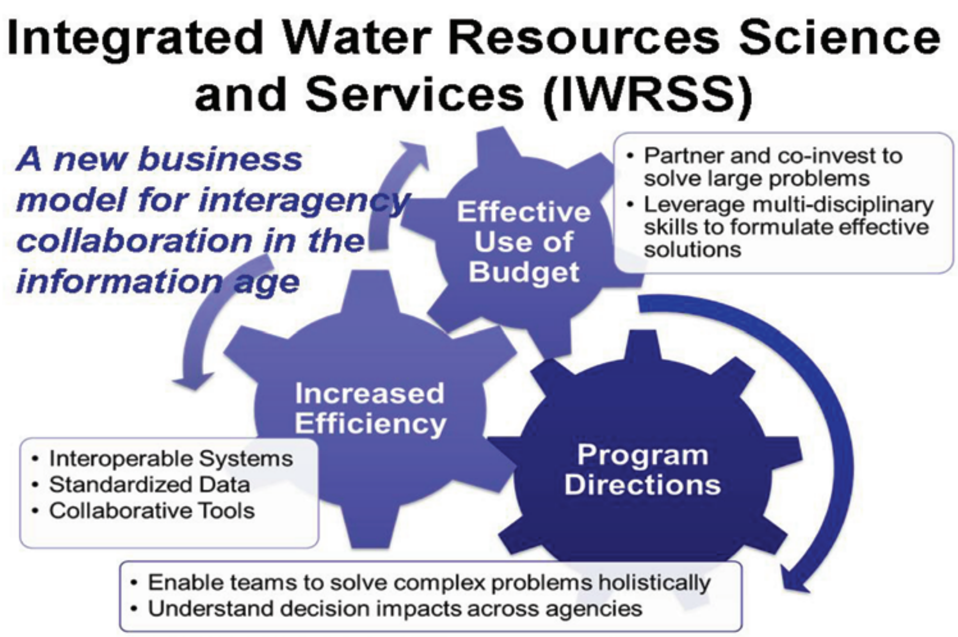


Figure 14. Overview of the Integrated Water Resources Science and Service Business Model.

Finding 24: Existing Coordination. Significant ecological and social benefits are expected from enhanced coordination of water-related data collection and integration of activities across the Federal government and with non-Federal partners.

global hydrologic cycle. The SWAQ focuses on science issues and associated policy options related to research and improvements in technology to advance the goal of ensuring a safe and sustainable supply of water in the United States in order to preserve the capacity to support societal and ecological needs, particularly in the context of a changing climate.

The Advisory Committee on Water Information (ACWI; *http://acwi.gov*) is a Federal Advisory Committee that represents the interests of water-information users and professionals. ACWI represents the interests of water-information users and professionals in advising the Federal Government on Federal water-information programs and their effectiveness in meeting the Nation's water-information needs. ACWI supports a number of subcommittees, including the Subcommittee on Spatial Water Data and the Sustainable Water Resources Roundtable, both of which are relevant to findings presented in the report. ACWI provides a neutral forum for collaboration on the collection, storage, management, analysis, and dissemination of climate-relevant water information.

Related to the coordinated use and application of water resources data and information for natural resources management, a committee was formed in 2010, in coordination with the Interagency Climate Change Adaptation Task Force and composed of Federal, state, and tribal partners, with input from many others, to develop a collective national adaptation strategy for fish, wildlife, and plant resources and their habitats. The committee's objective is to produce a National Fish, Wildlife, and Plants Climate Adaptation Strategy (NFWPCAS, 2011) by 2012 that identifies and defines principles and methods to maintain key terrestrial, freshwater, and marine ecosystems and functions needed to sustain fish, wildlife and plants. This blueprint for common action will outline needed scientific support, policy and legal frameworks; best management practices; processes for integration and communication; and a framework for implementing these approaches at regional and local scales.

Neither the SWAQ, ACWI, nor the NFWPCAS team currently are constituted to address all of the water-related challenges facing the Nation. These two entities, however, represent opportunities for improved coordination across Federal agencies and with Tribal, state, and local groups.

Next Steps

Effective management of the Nation's water resources will require meaningful action to address many of the shortcomings that were identified in this report on hydroclimatic observational and modeling systems. Moreover, continued vigilance and effort will be required to sustain and enhance vital observation and modeling systems that currently are in place and operating effectively over a period of years. Federal agencies should consider amending existing programs and policies to incorporate these actions whenever possible and should consider these actions in future budget planning.

This report does not prioritize among the needs that were identified, but prioritization will be required as Congress and the water-resources community begin to deliberate on these findings. Certainly, high priority should be given to maintaining existing capabilities, as measurements of hydroclimatic processes that are not made can never be recovered, creating unrecoverable gaps in the systematic record. Findings in this report that are supported by other documents (for example, the National Monitoring Network and the National Groundwater Monitoring Network) and those groups also deserve priority consideration.

Key next steps for Federal agencies to implement the findings of this report are described below.

1. **Strengthen observational data systems for freshwater resources and climate change.**

    - Strengthen existing efforts, including the Water Census, through enhancements to the hydroclimatic observational network identified in **Review Element 1** of this report. Information that is critical from a health, safety, and welfare perspective should be given priority, while

Finding 25: Existing Coordination Mechanisms. Federal agency actions towards improving data integration should continue and be accelerated through the Subcommittee on Water Availability (SWAQ) and the Advisory Committee on Water Information (ACWI). SWAQ should be strengthened to better promote cross-agency communication and additional coordination opportunities. The Advisory Committee on Water Information provides a useful, and perhaps under-utilized forum for collaboration on the collection, storage, management, analysis, and dissemination of climate-relevant water information between Federal and Tribal, state, and local agencies.

considering the data needs of land, water and environmental resource managers. Effects on water resources from energy extraction and production, and carbon sequestration (both geologic and biological) need increased emphasis.

- Conduct ongoing and sustained analyses of hydroclimatic data to identify emerging trends and patterns and to develop new insight into hydroclimatic variability.

2. Prioritize observational systems that fill important gaps in understanding water supply reliability.

- Enhance collection of water-use information, including provision of timely information on withdrawals and return flows (quantity and quality) from surface and groundwater resources and information on withdrawals and consumptive use by sector.
- Implement the proposed National Streamflow Information Program and the National Groundwater Monitoring Network, both of which are authorized in PL 111-11.
- Develop and implement a national lake/reservoir level and contents data network.
- In partnership with private industry, conduct research on new monitoring technologies, including sensors, data transmission, automated quality assurance, and remote-sensing technologies.

3. Improve water-quality and ecosystem monitoring systems.

- Implement the National Water-quality Monitoring Network, which is supported by the Advisory Committee on Water Information and is consistent with the National Ocean Council's Strategic Action Plans.
- Enhance interagency efforts and support States to monitor and improve mapping of wetland areas and habitat quality on a seasonal basis.
- Implement a waterborne disease tracking network, including all appropriate ancillary data.

4. Strengthen links between hydroclimatic observational data systems and climate models; improve data management, acquisition, analysis, and reporting.

- Link monitoring, observational systems, climate model outputs and other data systems, to update and improve hydroclimatic statistics that support high-priority water management decisions (particularly related to water supply reliability and quality).
- Build on the initial foundation established by the Integrated Water Resources Sciences and Services activity to expand and encourage the use of consistent data standards across agencies and with non-governmental partners and other ways to integrate existing data into more comprehensive water information systems.
- Develop new and improved models (both statistical and deterministic) for assessing hydroclimatic data, developing design conditions, and forecasting likely future conditions for expected scenarios.
- Develop guidance for water managers on appropriate use of probabilistic projections and model outputs.

5. Support the establishment of an interagency climate data portal and provide access to high priority water-related datasets.

- Promote interagency coordination of diverse data and define the architecture of data systems for freshwater resources to facilitate improved access to these data through a single portal. As a part of the portal, provide for user feedback, including recommendations for improvements or modifications.

6. Strengthen coordination to improve the quality and accessibility of freshwater data systems including technical outreach and support to stakeholders and decision-makers.

- Request that the Subcommittee on Water Availability and Quality (SWAQ) monitor progress on implementing the findings and recommendations of this report and provide annual updates to the National Science and Technology Council and member agencies, and to non-Federal partners.
- Promote interagency coordination and cooperation to implement the National Water Census (*http://water.usgs.gov/wsi/)* and Integrated Water Resources Science and Services (National Oceanic and Atmospheric Administration, 2009).
- Encourage the Advisory Committee on Water Information, an existing Federal Advisory Committee, to establish a new subcommittee or other appropriate mechanism, to solicit and consider input from the public and stakeholders on matters related to freshwater resources and a changing climate and relay these views to Federal water data program managers and the SWAQ.
- Fully engage States, Tribes, local agencies, and interstate organizations, most of whom have water-resources management responsibilities, in the implementation of the findings in this report.

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Acronyms

Acronym	Definition
ACWI	Advisory Committee on Water Information
ALI	Hyperion and Advanced Land Imager
ASOS	Automated Surface Observing System
ASTAR	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATTAINS	Assessment Total Daily Maximum Load Tracking and Implementation System
AVHRR	Advanced Very High Resloution Radiometer
BMPs	Best Management Practices
BoR	Bureau of Reclamation
CCAWWG	Climate Change and Water Working Group
CDC	Centers for Disease Control and Prevention
CEN	Climate Effects Network
CENRS	Committee on Environmental and Natural Resources and Sustainability
CHS	Canadian Hydrographic Service
CHPS	Community Hydrologic Prediction System
COOP	Cooperative Observer Program
CRN	Climate Response Network
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science Inc.
DOQQ	Digital Orthophoto Quadrangles
ELGs	Effluent Limitation Guidelines
EMAP	Environmental Monitoring and Assessment Program
FGDC	Federal Geographic Data Committee
FRS	Farm and Ranch Survey
GCMs	Global Climate Models
HIS	Hydrologic Information System
IWRSS	Integrated Water Resources Science and Services
ICCATF	Interagency Climate Change Adaptation Task Force
IOOS®	U.S. Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
LDCM	Landstat Data Continuity Mission
LIDAR	Light Detection and Ranging
MODIS	Moderate Resolution Imgaing Spectroradiometer
MMS	Modular Modeling System
NAPP	National Aerial Photography Program
NACC	National Assessment on Climate Change
NARS	National Aquatic Research Survey
NASA	National Areonautics and Space Agency
NASQAN	National Stream Quality Accounting Network
NAWQA	National Water-quality Assessment Program
NCDC	National Climate Data Center
NCCR	National Coastal Commission Report
NEP	National Estuary Programs
NEXRAD	Next-Generation Radar

Acronym	Definition
NFDM	Nations' Freshwater Data and Models
NFWPCAS	National Fish, Wildlife, and Plants Climate Adaptation Strategy
	National Health and Nutrition Examination Survey
NHAP	National High Altitude Photography
	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
	National Pollutant Discharge Elimination System
NPS	National Park Service
	Natural Resources Conservation Service
NSA	National Snow Analysis
	National Science Foundation
NSIP	National Streamflow Information Program
	National Science and Technology Council
NSQAP	National Stream Quality Assessment Program
	National Water Information System
NWS	National Weather Service
	National Water-Use Information Program
OSTP	U.S. Office of Science and Technology Policy
	Reservoir Sedimentation Database
RLLN	River and Lake Level Network
	Regional U.S. Historical Climate Network
SCAN	Soil Climate Analysis Network
	Safe Drinking Water Act
SMAP	Soil Moisture Active Passive
	Snowpack Telemetry
SRTM	Shuttle Radar Topography Mission
	Snow Survey and Water Supply Forecasting
STORET	Storage and Retrival Data Warehouse
	Subcommittee on Water Availability and Quality
TMDLs	Total Maximum Daily Loads
	Tennessee Valley Authority
UIC	Underground Injection Control
	U.S. Army Corps of Engineers
CRN	U.S. Climate Reference Network
	U.S. Department of Agriculture–Agriculture Research Service
USDA–FS	U.S. Department of Agriculture–Forest Service
	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
	U.S. Geological Survey
USGCRP	U.S. Global Change Research Program
	Wadeable Streams Assessment
WaterML	Water Mark-up Language
	Water Quality Criteria and Standards
WRCCW	Water Resources and Climate Change Workgroup

Appendices

Appendix A. SECURE Water Act: SEC. 9506. Climate Change and Water IntraGovernmental Panel

123 STAT. 1338 PUBLIC LAW 111–11—MAR. 30, 2009

SEC. 9506. CLIMATE CHANGE AND WATER INTRAGOVERNMENTAL PANEL.

(a) ESTABLISHMENT.—The Secretary and the Administrator shall establish and lead a climate change and water intragovernmental panel—

(1) to review the current scientific understanding of each impact of global climate change on the quantity and quality of freshwater resources of the United States; and

(2) to develop any strategy that the panel determines to be necessary to improve observational capabilities, expand data acquisition, or take other actions—

(A) to increase the reliability and accuracy of modeling and prediction systems to benefit water managers at the Federal, State, and local levels; and

(B) to increase the understanding of the impacts of climate change on aquatic ecosystems.

(b) MEMBERSHIP.—The panel shall be comprised of—

(1) the Secretary;

(2) the Director;

(3) the Administrator;

(4) the Secretary of Agriculture (acting through the Under Secretary for Natural Resources and Environment);

(5) the Commissioner;

(6) the Secretary of the Army, acting through the Chief of Engineers;

(7) the Administrator of the U.S. Environmental Protection Agency; and

(8) the Secretary of Energy.

(c) REVIEW ELEMENTS.—In conducting the review and developing the strategy under subsection (a), the panel shall consult with State water resource agencies, the Advisory Committee, drinking water utilities, water research organizations, and relevant water user, environmental, and other nongovernmental organizations—

(1) to assess the extent to which the conduct of measures of streamflow, groundwater levels, soil moisture, evapotranspiration rates, evaporation rates, snowpack levels, precipitation amounts, flood risk, and glacier mass is necessary to improve the understanding of the Federal Government and the States with respect to each impact of global climate change on water resources;

(2) to identify data gaps in current water monitoring networks that must be addressed to improve the capability of the Federal Government and the States to measure, analyze, and predict changes to the quality and quantity of water resources, including flood risks, that are directly or indirectly affected by global climate change;

(3) to establish data management and communication protocols and standards to increase the quality and efficiency by which each Federal agency acquires and reports relevant data;

(4) to consider options for the establishment of a data portal to enhance access to water resource data—

(A) relating to each nationally significant freshwater watershed and aquifer located in the United States; and

(B) that is collected by each Federal agency and any other public or private entity for each nationally significant freshwater watershed and aquifer located in the United States;

(5) to facilitate the development of hydrologic and other models to integrate data that reflects groundwater and surface water interactions; and

(6) to apply the hydrologic and other models developed under paragraph (5) to water resource management problems identified by the panel, including the need to maintain or improve ecological resiliency at watershed and aquifer system scales.

(d) REPORT.—Not later than 2 years after the date of enactment of this Act, the Secretary shall submit to the appropriate committees of Congress a report that describes the review conducted, and

the strategy developed, by the panel under subsection (a).

(e) DEMONSTRATION, RESEARCH, AND METHODOLOGY DEVELOPMENT PROJECTS.—

(1) AUTHORITY OF SECRETARY.—The Secretary, in consultation with the panel and the Advisory Committee, may provide grants to, or enter into any contract, cooperative agreement, interagency agreement, or other transaction with, an appropriate entity to carry out any demonstration, research, or methodology development project that the Secretary determines to be necessary to assist in the implementation of the strategy developed by the panel under subsection (a)(2).

(2) REQUIREMENTS.—

(A) MAXIMUM AMOUNT OF FEDERAL SHARE.—The Federal share of the cost of any demonstration, research, or methodology development project that is the subject of any grant, contract, cooperative agreement, interagency agreement, or other transaction entered into between the Secretary and an appropriate entity under paragraph (1) shall not exceed $1,000,000.

(B) REPORT.—An appropriate entity that receives funds from a grant, contract, cooperative agreement, interagency agreement, or other transaction entered into between the Secretary and the appropriate entity under paragraph (1) shall submit to the Secretary a report describing the results of the demonstration, research, or methodology development project conducted by the appropriate entity.

(f) AUTHORIZATION OF APPROPRIATIONS.—

(1) IN GENERAL.—There is authorized to be appropriated to carry out subsections (a) through (d) $2,000,000 for each of fiscal years 2009 through 2011, to remain available until expended.

(2) DEMONSTRATION, RESEARCH, AND METHODOLOGY DEVELOPMENT PROJECTS.—There is authorized to be appropriated to carry out subsection (e) $10,000,000 for the period of fiscal years 2009 through 2013, to remain available until expended.

Appendix B. Examples of existing networks that produce observational data relevant to climate change and water resources

- Streamgage network: approximately 7,500 streamgages (ref ACWI) where observations are made at specific time intervals that range from 15-minutes to 1-hour with data transmitted via satellite for dissemination to the public via the Internet
- Groundwater monitoring network
- Groundwater Climate Response Network
- Precipitation: Cooperative Observer Program (COOP), Automated Surface Observing System (ASOS), Snow Survey and Water Supply Forecasting (SS-WSF), and Snowpack Telemetry (SNOTEL), U.S. Climate Reference Network (CRN) and the Regional U.S. Historical Climate Network (RUSHCN)
- Water quality: National Water Information System (NWIS) includes surface water, groundwater, and water-qualitydata spanning all 50 States, plus border and territorial sites, and include data from as early as 1899 to present.
- Land remote sensing: Remote sensing products are developed by NASA, NOAA, USGS, and other Federal, State, and private sector partners using satellites and aircraft monitor the Earth. The satellite imagery and aerial photographs are archived and used to compare current conditions with historical land features. Data can be interpreted over time and space to assess the impact of natural disasters, climate, and other global changes. A summary of the components of the USGS Land and Remote Sensing (LRS) is provided in Appendix C and can be accessed on-line at *http://remotesensing.usgs.gov/*.
- National Stream Quality Accounting Network (NASQAN): concentrations and loads of selected constituents delivered by major rivers to the coastal waters of the United States and selected inland sub-basins in priority river basins to determine the sources and relative yields of constituents within these basins. These priority basins have significant management interest in reducing delivery of constituents that contribute to adverse conditions in receiving waters. Other objectives include monitoring for climate change and describing long-term trends in the loads and concentrations of select constituents at key locations.
- Nationally notifiable disease surveillance system
- National Health and Nutrition Examination Survey (NHANES): Collection of data on the health and nutritional status of a nationally representative sample of about 5,000 persons each year.
- Benchmark glacier monitoring *http://ak.water.usgs.gov/glaciology/*

Appendix C. Examples of current databases that incorporate information relevant to climate change and water resources

Observational data

- The Natural Resources Inventory (NRI): database of the status, condition, and trends of land, soil, water, and related resources on the Nation's non-Federal lands, which is maintained by USDA National Resources Conservation Service (NRCS). The data are collected yearly and continually updated and used by natural resource managers; policymakers and analysts; consultants; the media; other Federal agencies; State governments; universities; environmental, commodity, and farm groups; and the public. Much of the farm-scale data are not publicly available.
- National Water Information System (NWIS) database: database containing streamflow, water-quality, ground-water levels and quality, algal composition, quality of bed material, and composition of animal tissue.
- National Ambient Water-quality Assessment Program (NAWQA): Database of physical, chemical, and biological data from specific sites across the U.S.
- Storage and Retrieval Data Warehouse (STORET): repository for water quality, biological, and physical data and is used by State environmental agencies, EPA and other Federal agencies, universities, private citizens, and many others.
- Assessment Total Daily Maximum Load Tracking and Implementation System (ATTAINS): provides access to information on impaired waters.
- NOAA's National Weather Service interactive website (*http://water.weather.gov/ahps/*): provides easy access to data on weather, rainfall, snow, flood-stage status, hydrographs, digital tools to generate flood inundation maps
- National Streamflow Information database (NSIP)
- National Climatic Data Center: Maintains a broad range of national and global climate data sets, as well as model archives.

Aerial imagery maintained by the Land Remote Sensing Program

- National Aerial Photography Program (NAPP) - The National Aerial Photography Program is an interagency Federal effort coordinated by the USGS, which uses NAPP products to revise maps.
- National High Altitude Photography (NHAP) - The National High Altitude Photography (NHAP) program, which was operated from 1980-1989, was coordinated by the U.S. Geological Survey as an interagency project to eliminate duplicate photography in various Government programs.
- Digital Orthophoto Quadrangles (DOQQ) - Digital images of aerial photos which combine the image characteristics of the photo with the georeferenced qualities of a map
- Light Detection and Ranging (LIDAR) - LIDAR is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.
- Aircraft scanners - Digital imagery acquired from several multispectral scanners on board NASA ER–2, NASA C–130B, and NASA Learjet aircrafts
- Historical, commercial, and Scientific Committee on Antarctic Research (SCOR) imagery

Satellite imagery maintained by Land Remote Sensing Program

- Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTAR) - High-resolution multispectral data from the *Terra* satellite
- Advanced Very High Resolution Radiometer (AVHRR) - 1-km multispectral data from the NOAA satellite series
- Hyperion and Advanced Land Imager (ALI) - 10- to 30-meter multispectral and hyperspectral data from the Earth Observing-1 (EO-1) Extended Mission
- LANDSAT - Landsat satellites have been providing multispectral images of the Earth continuously since the early 1970's.
- Landsat ETM+ (Enhanced Thematic Mapper Plus)–High-resolution (15- to 60-meter) multispectral data from Landsat 7 (1999 to present)
- Landsat MSS (Multispectral Scanner) - 80-meter multispectral data from Landsats 1 to 5 (1972 to 1992).
- Landsat TM (Thematic Mapper) - 30- to 120-meter multispectral data from Landsat 4 and 5 (1982 to present).
- Landsat Data Continuity Mission (LDCM) - Multispectral data from the proposed Landsat Data Continuity Mission.
- Moderate Resolution Imaging Spectroradiometer (MODIS) - Moderate-resolution (250- to 1000-meter) multispectral data from the Terra Satellite (2000 to present) and Aqua Satellite (2002 to present).
- Shuttle Radar Topography Mission (SRTM) - SRTM data are used to generate a digital topographic map of the Earth's land surface with data points spaced every 1 arc second of latitude and longituded for the United States (approximately every 30 meters).
- SIR-C (Spaceborne Imaging Radar C-band) - Imaging radar data (C-band and L-band) from two Space Shuttle missions (1994).
- *Declassified Satellite Images - Category 1* - Photographic imagery from the CORONA, ARGON and LANYARD satellites (1959 to 1972).
- *Declassified Satellite Images - Category 2* - Photographic imagery from KH-7 Surveillance and KH-9 Mapping system (1963 to 1980).
- *USGS Commercial Data Purchases (UCDP) Imagery* - The UCDP Imagery Collection consists of imagery from several commercial vendors. The UCDP supports the *Commercial Remote Sensing Space Policy* (CRSSP) by providing data to qualified users, primarily U.S. Federal agencies, at no cost for File Transfer Protocol (FTP) downloads or at a nominal cost for media.

Appendix D. Major contributors to this report

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