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USGS Integrated Drought Science

Circular 1430

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By Andrea C. Ostroff, Clint C. Muhlfeld, Patrick M. Lambert, Nathaniel L. Booth, Shawn L. Carter, Jason M. Stoker, and Michael J. Focazio

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Project Need and Overview

Drought poses a serious threat to the resilience of human communities and ecosystems in the United States (Easterling and others, 2000). Over the past several years, many regions have experienced extreme drought conditions, fueled by prolonged periods of reduced precipitation and exceptionally warm temperatures. Extreme drought has far-reaching impacts on water supplies, ecosystems, agricultural production, critical infrastructure, energy costs, human health, and local economies (Milly and others, 2005; Wihlite, 2005; Vörösmarty and others, 2010; Choat and others, 2012; Ledger and others, 2013). As global temperatures continue to increase, the frequency, severity, extent, and duration of droughts are expected to increase across North America, affecting both humans and natural ecosystems (Parry and others, 2007).

The USGS is organized into seven Mission Areas that focus on some of the most significant issues facing society. Understanding drought processes will require capabilities from all the USGS Mission Areas including Water, Ecosystems, Climate and Land Use Change, Core Science Systems, Environmental Health, Natural Hazards, and Energy and Minerals.

The U.S. Geological Survey (USGS) has a long, proven history of delivering science and tools to help decision-makers manage and mitigate effects of drought. That said, there is substantial capacity for improved integration and coordination in the ways that the USGS provides drought science. A USGS Drought Team was formed in August 2016 to work across USGS Mission Areas to identify current USGS drought-related research and core capabilities. This information has been used to initiate the development of an integrated science effort that will bring the full USGS capacity to bear on this national crisis.

Goals and Objectives

To address the issue of drought and build long-term resilience to drought at local, regional, and national levels, the USGS has developed a coordinated and integrated drought science plan. The plan presents a new path for understanding the complexity of drought issues and the impact of drought on human and natural systems. This understanding can inform policy and decision-making for adaptation and mitigation. The primary objectives of the USGS Integrated Drought Science Plan introduced in this document are to increase coordination among Mission Areas and to demonstrate the potential of broadened integration of USGS capacities for comprehensive response to stakeholders' needs. Ultimately, the desired outcomes of USGS integrated drought science are to gain additional practicable understanding of complex interactions that determine drought and drought effects; describe uncertainties associated with drought causes and effects; develop robust models to predict drought risk and vulnerability for planning and mitigation purposes; advance efforts in coordinated drought science that will lead to development of drought-monitoring systems; and deliver decision-support science to help Federal, State, Tribal, regional, and local stakeholders prepare and manage for the future across the United States.

The **USGS Integrated Drought Science Plan** *seeks to improve understanding of drought processes and impacts on human and natural systems through coordinated and multidisciplinary data collection, synthesis, analysis, and predictions generated from USGS Mission Areas and various partnerships. The goal is to provide decision-support tools and technologies to stakeholders for enhancing drought resilience, adaptation, and mitigation.*

USGS Role in Federal Drought Resilience Plan

Drought is a prolonged and widespread deficit in available water supplies that may cause substantial economic or social impacts, or physical damage or injury to individuals, property, or the environment (Wihlite, 2005). Droughts can be defined in four ways:

- Meteorological drought is below-normal precipitation,
- Hydrological drought is below-normal availability of surface water and groundwater,
- Agricultural drought is various characteristics of meteorological and hydrological drought applied to agricultural effects, and
- Ecological drought is deficits in natural water availability that create multiple stressors across ecosystems.

Impacts of drought are complex and multifaceted, but generally can be classified as economic, environmental, and social. Human population growth, additional land and water uses by people, and global warming are expected to exacerbate the frequency and severity of future droughts in many regions of the United States (Easterling and others, 2000). In response, the Federal Government has introduced new measures to help the United States anticipate and cope with drought by focusing on short-term and long-term drought-resilience issues.

Summary of Key Goals and Strategies

Data Collection and Integration

- Strengthen data observation and monitoring networks to maximize spatial and temporal coverages, provide reliable operation and near-real-time delivery, increase interoperability of networks among agencies, and improve early warnings.
- Improve data collection during and after drought events to gather critical, time-dependent information.
- Develop and advance new monitoring tools and technologies.
- Facilitate citizen science for crowdsourced data related to water availability.

Understanding Drought Processes and Impacts

- Synthesize datasets and models to improve understanding of factors that cause drought and how they interact with one another, and how systems respond to drought.
- Promote and conduct targeted research addressing drought processes, extreme events, impacts, risk, and response.
- Develop robust models to predict drought risk and vulnerability for decision-making.
- Examine and synthesize ecological impacts of drought for conservation management.
- Promote multi-disciplinary research, integrated assessments, predictive modeling, and knowledge transfer to address drought complexity and uncertainty.
- Identify the unintended consequences of drought management leading to environmental pathways of contaminant exposures to humans and other organisms.

Drought Planning and Decision Support

- Predict future drought vulnerability of species and ecosystems with comprehensive understanding of drought processes, ecosystem impacts, and recovery times.
- Deliver decision-support guides that link research, monitoring, forecasting, and early warning with risk planning and management.
- Provide technical assistance to address stakeholders' needs.
- Create and deliver effective multimedia to communicate drought through partnerships with stakeholders, decision-makers, and the public.
- Produce knowledge products that inform decisions to minimize risk of contaminant exposures.

In 2013, the Federal Administration established the National Drought Resilience Partnership (NDRP), an interagency Federal working group initiative, as part of the national Climate Action Plan. The NDRP was formed to advance national-level drought-resilience capabilities by helping communities prepare for and mitigate the impacts of drought on livelihoods and economies. A 2016 Presidential Memorandum directed Federal agencies to build national capabilities for long-term drought resilience using existing resources and under existing authorities (The White House, 2016). The memorandum also tasked the NDRP to deliver a Federal action plan to promote drought resilience nationwide.

The *Long-Term Drought Resilience Federal Action Plan* (Action Plan) specifies six goals and corresponding actions for each goal. The goals are:

Goal 1: Data Collection and Integration
Goal 2: Communicating of Drought Risk to Critical Infrastructure
Goal 3: Drought Planning and Capacity Building
Goal 4: Coordination of Federal Drought Activity
Goal 5: Market-Based Approaches for Infrastructure and Efficiency
Goal 6: Innovative Water Use, Efficiency, and Technology

Furthermore, the Action Plan outlines how NDRP Federal agencies can use existing authorities to work with State, Tribal, regional, and local partners to respond to drought and implement strategies for long-term resilience.

The USGS is identified as a lead or supporting Federal agency to implement a number of actions under three goals of the Action Plan (fig. 1). The first goal, **Data Collection and Integration**, aims to *integrate existing data and information sources for regional-level use by integrating data from key platforms*. The USGS serves as a lead coordinating agency for data integration from key platforms. Accomplishments associated with this implementation action will help assess, strengthen, and connect existing space-based, airborne, and terrestrial data-collection and monitoring capabilities, such as surface-water and groundwater quantity and quality, snowpack, soil moisture, and biological datasets. This integration also helps to make data and information easily accessible. The USGS was identified to serve a supporting role to **Communicating Drought Risk to Critical Infrastructure** through development of drought decision-support systems for critical infrastructure stakeholders. The USGS was specifically named as a supporting agency for **Drought Planning and Capacity Building** by enhancing national data coverage through citizen science, developing models to identify and predict ecosystem and human-health risks for specific locations and populations, and examining ecological impacts of drought across the United States.

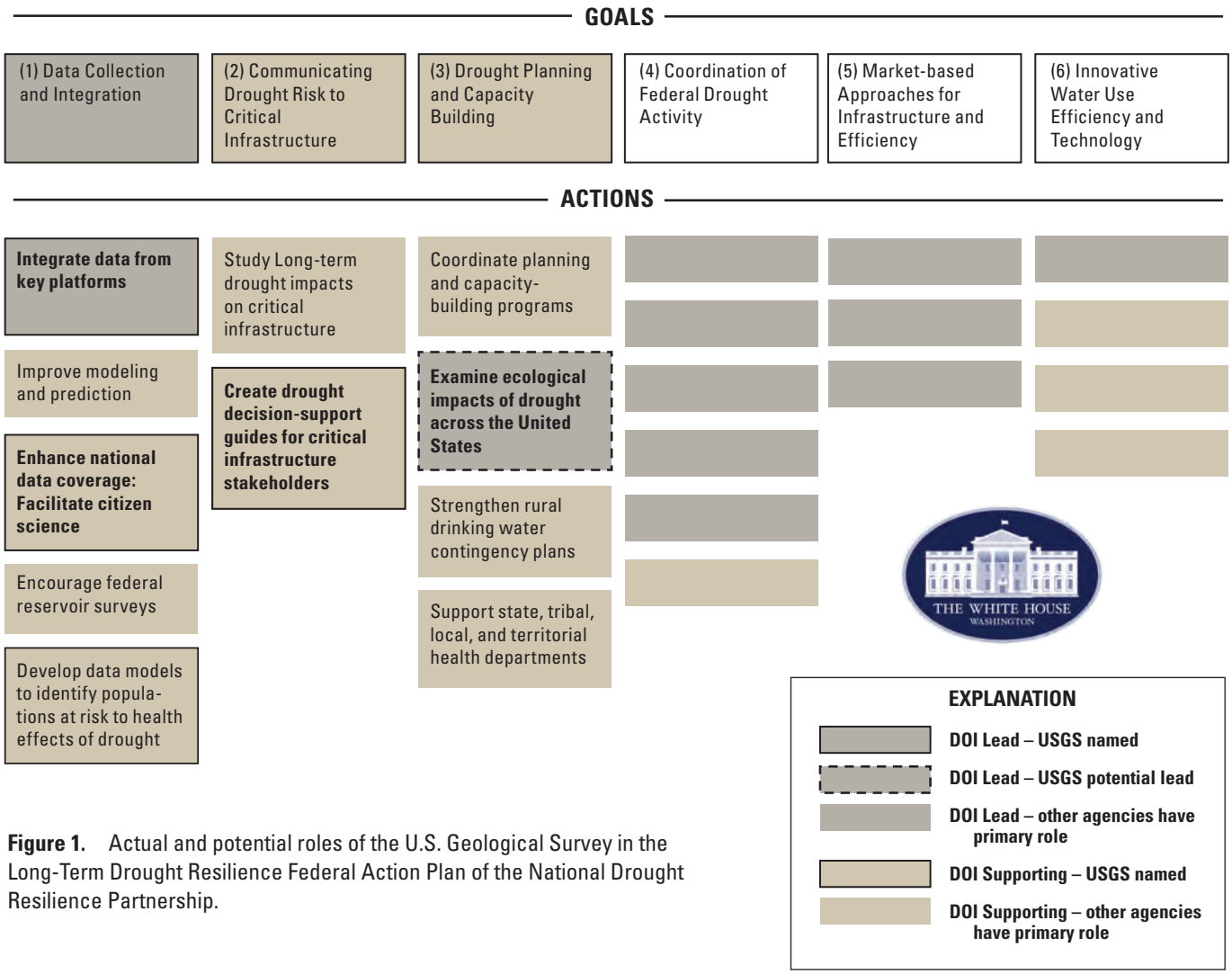


Figure 1. Actual and potential roles of the U.S. Geological Survey in the Long-Term Drought Resilience Federal Action Plan of the National Drought Resilience Partnership.

Current USGS Drought Projects and Capabilities

The broad expertise of USGS researchers and the engagement of regional and local USGS administrators and scientists with local and regional stakeholders facilitate broad response to all six goals in the Action Plan. Here, a number of notable examples of existing USGS projects and products are highlighted for each of the three goals where the USGS is specifically named as a lead or supporting agency. This sampling of projects and products is by no means comprehensive, but demonstrates the breadth and scope of USGS drought-related research and monitoring.

GOAL 1: Data Collection and Integration

Objective: Agencies shall share data and information related to drought, water use, and water availability, including data on snowpack, groundwater, streamflow, and soil moisture, with State, regional, Tribal, and local officials to strengthen decision-making to support more adaptive responses to drought and drought risk.

Groundwater and Streamflow Information Program: Measuring and assessing the Nation's water resources through basic hydrologic monitoring, providing foundational information for preparation and response to drought. Assessment and integration of these nationwide datasets define the current status and recent trends in surface-water supply and groundwater storage.

Western Drought Resilience Assessment: Assessing streamflow resilience and drought susceptibility at more than 2,500 monitoring locations in the Nation's Western Basins. Goals for this fine-scale information program include documenting the severity of ongoing Western drought and assessing watershed sensitivity to drought, including reduced baseflows and increased water temperatures.

Regional Groundwater Assessments—Central Valley of California Groundwater—Availability Project: Applying detailed USGS hydrologic-system computer models to assess how the current California drought affects hydrologic conditions and subsidence in the Central Valley of California.

Western Mountain Initiative: Documenting responses of forests in the Western United States to disturbance and changing climate, evaluating vulnerability of forests to disturbance and drought, and evaluating forest response to hydrologic variability and drought.

Ecohydrological Research and Monitoring Networks in the Rocky Mountains: Using novel methods, collecting data about streamflow, water temperature, and biology across stream networks in the Rocky Mountains to understand effects of climatic variation and drought on native trout populations and other aquatic organisms including organism interactions with invasive species. Results can be used to design optimal strategies for investing in future monitoring and modeling of aquatic ecosystems.

National Amphibian Research and Monitoring Initiative (ARMI): A National cooperative program of amphibian monitoring and research led by the USGS to support conservation. Scientists study status and trends of amphibian populations and their life histories, measure and monitor environmental characteristics, and research potential causes of decline to inform management across the United States.

Vegetation Drought Response Index (VegDRI) Tool: Drought-monitoring tool that produces maps every 2 weeks that combine satellite-based observations of vegetation conditions with climate and environmental data to provide drought information for the United States.

Global Croplands Project: Using remote-sensing data, especially Landsat data, to map cropland extent and crop types, to support managing water supplies for both energy and food production to advance global food security.

Essential Climate Variables: Developing research-quality operational products using historical, current, and future Landsat data. The terrestrial variables represent specific geophysical and biophysical properties of the land surface, including extent of surface water, burned area, snow-covered area, and biomass, all useful for evaluating drought effects on terrestrial ecosystems.

Remote Sensing Monitoring of Irrigation Water Use: Conducting remote sensing of evapotranspiration amounts and vegetation health to allow for the quantification of water used in agricultural production and effects of use levels on yields. This research supports improved understanding of vegetation dynamics and relationships between croplands, drought, water, and food security. The USGS is working to test and implement these approaches in the United States and globally (USAID Famine Early Warning System).

National Land Cover Database (NLCD): Serves as the definitive Landsat-based, 30-meter resolution, land-cover database for the Nation. Providing spatial reference and descriptive data for characteristics of the land surface, such as thematic class (urban, agriculture, and forest), percent impervious surface, and percent cover of tree canopies.

USA National Phenology Network: As a consortium member, collecting, sharing, and using phenology data, models, and information to promote a broad understanding of plant and animal phenology and associations between phenology and environmental change. Professionals and "citizen scientists" collect phenological observations that are integrated and used to inform decision-making, including drought monitoring.

Monitoring Trends in Burn Severity Project: Providing a national analysis of trends in burn severity for the National Fire Plan. Because of severe droughts and greater-than-normal numbers of catastrophic fires since 2000, it is important for the trend analysis to account for potential climate variability and to base the assessment on a longer period of time than the last several years.

USGS National Brackish Groundwater Assessment: Identifying and characterizing significant brackish aquifers and water supplies in the United States. Development of brackish groundwater as an alternative water source for suitable uses can help address concerns about the future availability of water as demands increase in the face of climate variability and potentially intensifying periods of drought.

WaterWatch: Providing Web-accessible maps, graphs, and tables describing real-time, recent, and past streamflow conditions for the United States, including locations where extreme hydrologic events are occurring, such as floods and droughts.

Landsat Archive and Access: Providing continuous global Earth-observing data. This includes data collected for more than 40 years and that serve as the foundation for large-scale land-cover mapping to detect land change over time.

GOAL 2: Communicating Drought Risk to Critical Infrastructure

Objective: Agencies shall communicate with State, regional, Tribal, local, and critical infrastructure officials, targeted information about drought risks, including specific risks to critical infrastructure.

Developing a Coastal Salinity Drought Index: Characterizing the salinity-dynamics response in the Carolina coastal regions to drought using real-time and historical USGS salinity datasets and data-collection programs.

Climate Change Effects on Hydrologic Cycle—Effect of Drought on Runoff from Snow: Investigating changes in runoff from winter snowpack in the Rocky Mountains. Pacific ocean-atmosphere variability and trends are tracked to assess their effects on decadal variability in snowpack runoff in these mountains.

Groundwater Discharge Vulnerability to Drought: Examining short-term response of groundwater systems to climate stresses, including drought at a regional scale, by assessing groundwater age. The project develops tools to identify areas of groundwater vulnerable to drought and climate variability within the basin of interest.

Tree Growth in Swamps across Drought and Salinity Gradients along the Northern Gulf Coast: Examining potential effects of climate-change-induced sea-level rise, drought, and water extraction using tree-growth patterns across the Gulf Coast, specifically targeting long-term research plots in the North American Bald Cypress Swamp Network and the Suwannee River.

Understanding Effects of Climate Change on Hawaiian Plants: Developing vulnerability models and conducting experiments to assess current and future ecological and evolutionary responses of Hawaiian plants associated with climate change and sea-level-rise predictions. This research considers more than 1,000 species, including 319 protected under the Endangered Species Act.

Drought and Fish Disease in the Pacific Northwest: Assessing mass mortalities of salmon, sturgeon, trout, and whitefish from disease in areas of the Pacific Northwest. Results will be used to predict how future hydrologic and thermal conditions experienced during extreme droughts may impact fishes of socioeconomic, cultural, and ecological importance in the Western United States.

Climate Change and Ecological Drought Impacts on Dryland Ecosystems: Conducting research in the arid Southwest to understand spatiotemporal patterns of increasing aridity on soil moisture and effects on ecosystem structure and function, including effects on plants, soils, biological soil crusts, microbial communities, biogeochemical cycles, plant-soil interactions, and vegetation dynamics.

Drought and Fire: Investigating the processes of drought as a stressor that can enhance wildfire activity, which in turn, can affect vegetation and soil organic-matter recovery after wildfire. The project also assesses post-wildfire hyper-dryness impacts on infiltration rates, soil-water content, and vegetation recovery.

Regulated River Flow Assessments: Working with stakeholders in the Columbia and Colorado River Basins to manage dams for power generation, water supplies, flood risk management, and recovery of fish (salmon, steelhead, trout, sturgeon), wildlife, and ecosystem processes during periods of drought and decrease summer flows.

Groundwater and Temperature Modeling for Eastern Native Trout: Developing models that account for groundwater influences on thermal sensitivity to forecast climate change effects on stream temperature and native brook trout thermal habitat within forested watersheds in eastern North America.

Land Change Monitoring, Assessment, and Projection: Providing continuous, structured, operational, and timely collection and delivery of analysis-ready Earth-observing data, information, and knowledge on land use, cover, and condition. This project evaluates climate change and drought impacts on land change.

Long-Term Patterns of Natural Hydroclimate Variability: Useing paleo-climate data to document and synthesize patterns of long-term hydroclimate change across the Nation. Products can be used to evaluate the performance of climate models that predict future temperature and rainfall patterns.

Drivers of Drought: Using remote-sensing technologies to identify deviations from normal conditions in ecosystems that indicate threats to vulnerable communities in the form of drought, floods, disease outbreaks, or other hazards.

Holocene Hydroclimate of Western North America: Developing paleoclimate archives of temperature, precipitation, and corresponding environmental change that extend through the Holocene, including temporal variability and spatial patterns.

Paleohydrology of Desert Wetlands: Determining the hydrologic response of springs and desert wetlands to abrupt climate change events. The focus is to reconstruct changes in water-table levels in desert wetlands during the late Quaternary using wetland deposits exposed in outcrops and by sampling existing wetlands.

Impacts of Drought on Fish and Wildlife in the Southwest: Improving knowledge of individual behavioral changes (for desert bighorn sheep) and overall population changes (for pronghorn, trout, and quail) that occur in response to drought.

Effects of Drought on Vegetation Phenology and Migratory Wildlife: Assessing interactions among organisms and their environment, including how drought influences vegetation phenology, to better understand the potential effects on herbivores.

Assessing Impacts of Drought on Migratory Waterbirds in Key Western Conservation Regions: Examining potential impacts of drought on wetland-dependent migratory waterbirds in the Central Valley and interior basins of the Western United States.

GOAL 3: Drought Planning and Capacity Building

Objective: Agencies shall assist State, regional, Tribal, and local officials in building local planning capacity for drought preparedness and resilience.

Hydrologic Cycle and Water Supply—Atmospheric Rivers: Investigating relevance of naturally occurring parts of the global water cycle on drought prediction and persistence in the Western United States. Investigating atmospheric rivers as pathways of water vapor and their impact on water supply and role as drought busters.

Drought Preparedness and Risk Reduction in Russian River Watershed, California: Evaluating drought-related precipitation characteristics and prediction to aid in drought planning in the Russian River Watershed, including appropriate balancing of water supply and flood-management operations through informed operation of regional storage infrastructure.

Stream Drying in the Western United States: Using remote-sensing data, temperature records, citizen science, and fish surveys to assess and predict streamflow permanence and drought conditions in the Great Basin and Pacific Northwest. The project develops planning tools to link water quality, land use, and conservation of sensitive species (native trout, amphibians, song birds, and greater sage-grouse).

Science for Nature and People Partnership (SNAPP) Ecological Drought Working Group: In a collaborative setting, defining ecological drought and developing applications for drought adaptation that bolster intact, functioning ecosystems that benefit people and nature.

Water, Energy, and Biogeochemical Project: Documenting the effects of hydrologic variability and landscape changes on hydrologic and biogeochemical fluxes in five small watersheds representing a range of ecosystems. This research supports effort to inform the public, government, and land managers about issues concerning water supplies and provides specific guidance to identify effective responses.

Coastal Ecosystem Response to Climate Change: Assessing the vulnerability of nearshore habitats and their dependent wildlife along the Pacific coast from sea-level rise and episodic storms. This interdisciplinary research program supports coastal land managers and policy makers who are developing adaptation plans for nearshore habitats to sustain ecosystem functions and services, such as fish and wildlife habitat, recreation, and flood protection.

New Jersey Drought Watch: Providing local-to-regional hydrologic monitoring, data synthesis, and dissemination for assessing drought indicators for regional water-supply sources. In a collaboration involving the USGS and the State of New Jersey, drought indicators are developed and conveyed to decision makers by integrating data from streamgages, low-flow partial record streamgages, and continuous-record and groundwater measurements.

USGS Science Application for Risk Reduction (SAFRR): Examining how water supply is stressed in the Southwest and how other climate-related extremes, such as forest fires, landslides, longer heat waves, sea-level rise, and more extreme storms, might influence non-water-supply sectors and how they could affect resilience to other natural hazards.

Understanding the Ecological Impacts of Drought across the United States: Synthesizing knowledge related to the regional impacts of ecological drought among all U.S. Department of the Interior Climate Science Centers, and developing tools and products that are relevant for decision-making.

Stakeholder Needs

Through this planning effort, information is gathered about key stakeholders concerned with drought-related issues and their needs from all regions of the United States. Primary stakeholders include Federal agencies, such as the U.S. Fish and Wildlife Service, National Park Service, Bureau of Land Management, Bureau of Reclamation, Army Corps of Engineers, National Oceanic and Atmospheric Organization (NOAA), U.S. Environmental Protection Agency (EPA), and U.S. Forest Service; State agencies, such as departments of natural resources, fish and wildlife, public health, and water resources; cities and counties; hydropower companies; farmers, landowners; and Tribes. A review of nationwide stakeholder-identified needs in the West and East reveals several commonalities. These can be aggregated into three key needs: drought monitoring and modeling, identifying drought impacts, and facilitating drought planning.

Drought Monitoring and Modeling

Nationwide, stakeholders emphasize the importance of data collection and monitoring to characterize water supplies, understand drought-risk conditions, and reveal unintended consequences of mitigation scenarios. These outcomes can be achieved by developing new approaches to adapt existing monitoring systems, such as the USGS Groundwater and Streamflow Information Program and the National Integrated Drought Information System, so they can better address stakeholder needs. These types of data can be used to monitor current conditions and as indicators for drought forecasting. Although drought monitoring is already relatively commonplace, stakeholders emphasize the importance of continuing to collect these data, improve monitoring and modeling techniques, and make data and information easily accessible and compatible with geospatial data platforms.

Drought forecasting in light of the uncertainties posed by climate change.

Understanding potential frequency, duration, and spatial extent of future droughts to enable managers of natural resources and water utilities to better prepare and enhance resiliency of ecosystems and communities.

Understanding groundwater effects on streamflow and temperature regimes.

Developing predictive models to identify areas most vulnerable to drought and to understand how climate change may alter drought conditions.

Monitoring important drought variables, including stream discharge, groundwater flows, soil moisture, and water reuse.

Monitoring and predicting stream temperatures and groundwater-influenced stream reaches to identify aquatic habitats that provide coldwater refuge for at-risk species of aquatic life.

Prioritizing streams for habitat protection and restoration, with consideration of future conditions anticipated with climate change.

Predicting areas susceptible to future wildfires and megadroughts.

Monitoring and predicting drought effects on disease outbreaks and impacts to fish populations.

Developing improved monitoring capabilities for early warning.

Drought Impacts

Across the nation, stakeholders seek an improved understanding of how drought affects fish and wildlife (particularly threatened and endangered species), ecosystems (terrestrial and aquatic), and the human communities that depend on ecosystem services to meet municipal, agricultural, industrial, and recreational water needs. This question is of particular concern to communities and Tribal sovereigns that rely on fish as a major subsistence food-source, as well as to State and Federal agencies in the West concerned with protecting endangered salmon and managing recreational and commercial fisheries.

Potential impacts of drought on water availability and quality as it relates to water supplies, production, opportunities, ecosystem services, and how these competing demands may be balanced during drought.

In coastal areas, information about drought and the potential for increased saltwater encroachment due to reduced freshwater flushing. Saltwater encroachment could have consequences for potable water supplies and the ability to release treated wastewater into rivers.

Potential exposures to environmental contaminants associated with water reuse activities, shifting patterns in use of pesticides and other land-applied chemicals, and movement and inhalation of dust.

Impacts of drought on water availability, particularly on critical water sources, such as the Colorado and Columbia Rivers.

Understanding how drought influences wildfire regimes, forest pests, such as pine bark beetles, and sensitive habitats, such as sagebrush and pinyon-pine systems.

Understanding how drought-induced reductions in stream flows, increases in water temperatures, and disease outbreaks affect fish, particularly coldwater species.

Understanding drought effects on species of concern, namely salmon and trout, amphibians, bats, grassland birds, prairie dogs, and pronghorn.

Drought Planning

Drought monitoring and drought assessment are critical steps towards addressing a major stakeholder need—determining what actions should be taken to plan for and mitigate drought effects and risks. Stakeholders nationwide are eager for decision support that will help them to proactively protect and prepare ecosystems and communities for drought—particularly in light of the uncertainties posed by climate change.

Assessing whether current water-storage capacities will be sufficient to meet multiple demands under different drought scenarios.

Assessing whether systems for water treatment and distribution will be able to withstand drought.

Considering new development alternatives, such as green infrastructure, to improve water conservation strategies.

Understanding how to best plan for agricultural, meteorological, hydrological, and ecological effects of drought.

Balancing effects on salmon and trout populations with competing human and ecological demands for water.

Understanding if reuse water will meet municipal water supply needs, and if so, how to minimize exposure pathways to environmental contaminants in reuse waters.

Identifying streams most vulnerable to drought to help guide stream restoration and conservation efforts.

Determining if reservoir and dam operations will be sufficient to meet future water, electricity, and fish-conservation needs.

Understanding if practices of land and water use for farming and grazing need to be altered in response to increasing water stress.

USGS Mission Area Capabilities

USGS science focuses on some of the most significant issues facing society and ecosystems in the United States and the Earth. USGS science addresses seven topics:

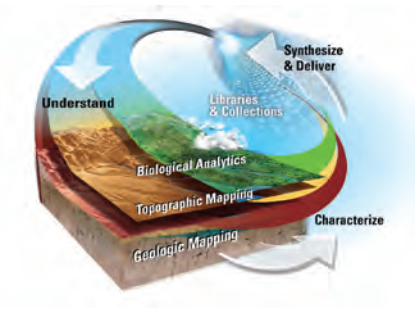
- Water
- Ecosystems
- Climate and Land Use Change
- Core Science Systems
- Environmental Health
- Natural Hazards
- Energy and Minerals

Within this context, the USGS has a long and proven history of addressing drought-related issues through data collection and integration, assessing drought impacts, and delivering key science to inform decision making. These core strengths and capabilities are consistent with the primary roles of the USGS in the NDRP and key stakeholders and their information needs.

The Water Mission Area conducts research and provides information and understanding of groundwater and surface-water resources, and the integrated nature of the hydrologic system that enables informed preparation for and response to drought. Improved understanding begins with consistent and continuous collection and dissemination of hydrologic data. The USGS and its cooperators measure groundwater levels annually in more than 21,000 wells, and monitor streamflow at more than 7,500 streamgages across the country. These systems provide knowledge of the range of variations in streamflow, and the reliable yield of reservoirs and aquifers. These data are made more useful through synthesis and incorporation into integrated hydrologic models capable of simultaneously accounting for changing water supply and demand, and simulating surface-water and groundwater occurrence and flow at a range of scales. Research and applied science programs also focus on the underpinnings of such modeling and decisions-support tools, including assessment of drought triggers and understanding and defining the physical characteristics of impacted hydrologic systems. Combined, these data products, research, and assessment tools inform the current and potential future status of water supplies and test the consequences to water users and ecosystems of plausible future drought scenarios.

The Ecosystems Mission Area conducts drought-related research and monitoring in freshwater, terrestrial, and marine ecosystems, commonly with specific studies of fish and wildlife inhabiting these ecosystems. Scientists work extensively with partners to collect and disseminate scientific and statistically reliable biological and ecological data to address drought-related scientific and management questions. Ecosystem scientists use this information and innovative technologies to synthesize, analyze, and model drought processes and biological responses to understand the causes and associated impacts of drought on aquatic and terrestrial ecosystems. By integrating climatic, physical, and biological data with emerging approaches in landscape ecology, researchers are quantifying and modeling drought impacts and risk to native plants and animals, invasive species, disease outbreaks, forest health, biogeochemical processes, fire regimes, and communities across the Nation. These biological data, research products, and assessment tools help guide strategic natural resource planning and mitigation strategies for sound conservation and management of biological resources in the face of increasing threats from drought.

The Climate and Land Use Change Mission Area conducts research that looks at how changes in climate and land use influence patterns of drought and how drought impacts natural resources. Scientists work extensively with partners to link both short- and long-term climate-driven drought to impacts on environments. Understanding of natural and human-induced changes in the hydrologic cycle encompasses monitoring, analyses of instrumental records of precipitation, streamflow and water quality, through reconstruction of pre-instrumental hydrology using paleoclimate data and modeling. Scientists working on climate and land-use issues combine these areas of data analyses with modeling to understand the potential rates of hydrologic change, natural patterns of variability, and the observed impacts of hydrologic change on ecosystems and societies. Scientists also are working to deliver a comprehensive assessment of the ecological impacts of drought and to inform efforts to reduce the risks facing nature and people. Scientists are developing methods to understand ways in which human communities can adapt to the long-term effects of drought by supporting healthy ecosystems. Findings from the Climate and Land Use Change Mission Area are synthesized to help inform local communities, businesses, and conservation practitioners.



The Core Science Systems Mission Area delivers nationally focused Earth systems and information science that provides fundamental research and data that underpins all USGS research. Although not directly involved in stand-alone drought-focused research, The Core Science Systems Mission Area builds and provides foundational, authoritative base data that are used across many components of other USGS drought research, including the National Hydrography Dataset and the 3D Elevation Program. One of the core competencies of the Core Science Systems Mission Area is to build and facilitate partnership and innovation across the USGS—a key capability for integrating disparate research efforts. The Core Science Systems Mission Area facilitates multiple USGS activities in support of data integration and synthesis, including the John Wesley Powell Center for Analysis and Synthesis, the Community for Data Integration, and ScienceBase.

The Environmental Health Mission Area supports research at the interfaces between health and environment. Focused on environmental pathways and exposures of chemical and microbial contaminants to humans and other organisms, scientists have broad laboratory and field capabilities in the science of sources, fate and transport, exposure, toxicity, and related adverse health effects on biota. Working in collaboration with public health agencies and experts in human health, the Environmental Health Mission Area provides datasets, interpretive products, and expertise in environmental contaminants that add value to epidemiological, cohort, and other studies. Current and planned research topics related to drought science and management include environmental exposures to pesticides and the relation to health (presumed to shift in usage patterns as drought stressors on agricultural crops increase), contaminant exposures and relations to health due to reuse of wastewaters (presumed to increase with the need for novel water sources for irrigation, artificial recharge, etc.), movement and exposures to contaminants associated and transported by dust (presumed to increase as soil moisture decreases) and its relation to health. Other capabilities include detailed investigations of environmental contaminant exposures through tapwaters, and the relations to health if groundwater and surface-water quality degrade.

The Natural Hazards Mission Area works with many partners to monitor, assess, and conduct targeted research on a wide range of natural hazards so that policy-makers and the public have the understanding they need to enhance preparedness, response, and resilience. USGS scientists conduct research and assessments to understand hazardous processes, including sources and impacts, and interactions with climate change to identify and predict hazards. Drought-relevant expertise includes methodologies for risk assessment and translation of the best-available science to decision-making. Comprehensive evaluation of the vulnerability of critical water supplies and water-dependent infrastructure requires consideration of potential impacts from all hazards. The Natural Hazards Mission Area also provides capabilities to describe and forecast persistent and extreme-event processes that alter the physical, geochemical, and ecological condition of coastal landscapes. In addition, the Natural Hazards Mission Area has expertise in developing scenarios that can explore the cascading social, ecological, and economic consequences of environmental crises.

The Energy and Minerals Mission Area conducts research and assessments on mineral and energy resources, including the economic and environmental effects of resource extraction and use. As climate warming ensues over the coming decades, science leading to a broad understanding of energy and mineral resources will be paramount for decisions supporting and protecting the economy, natural resources, and quality of life in the United States.

Integrated Drought Science Approach

Drought Resilience and Adaptation Planning has emerged as a powerful management tool to help prepare for and cope with the current and projected impacts of drought on ecosystem dynamics and services. Developing comprehensive and effective long-term drought-resilience and risk-management strategies requires improved understanding of the processes leading to drought and understanding the potential impacts and associated uncertainties of ongoing and future drought.

USGS Drought Science provides an adaptive science framework *to observe, synthesize, model, forecast, and deliver* decision-support guidance to address current and future drought and stakeholder needs, while *monitoring, revising, and improving technologies* to advance drought science in a changing world. The USGS has enormous strengths and capabilities to address drought issues directly or indirectly at regional and national levels, providing tremendous capacity to begin linking key science components across Mission Areas for an integrated and coordinated approach to drought science. These core strengths and capabilities contribute to drought understanding and coordination with regard to:

- Scientific understanding of drought processes and impacts
- Drought risk planning and prediction
- Provision of decision support to address current and future stakeholder needs
- Evaluation of outcomes from drought management

Through initial understanding of common stakeholder needs nationwide, the USGS developed a step-wise approach to underpin the USGS Integrated Drought Science Plan (fig. 2). The approach will enable improved knowledge transfer and facilitate USGS response to specific actions identified in the Long-Term Drought Resilience Federal Action Plan, through:

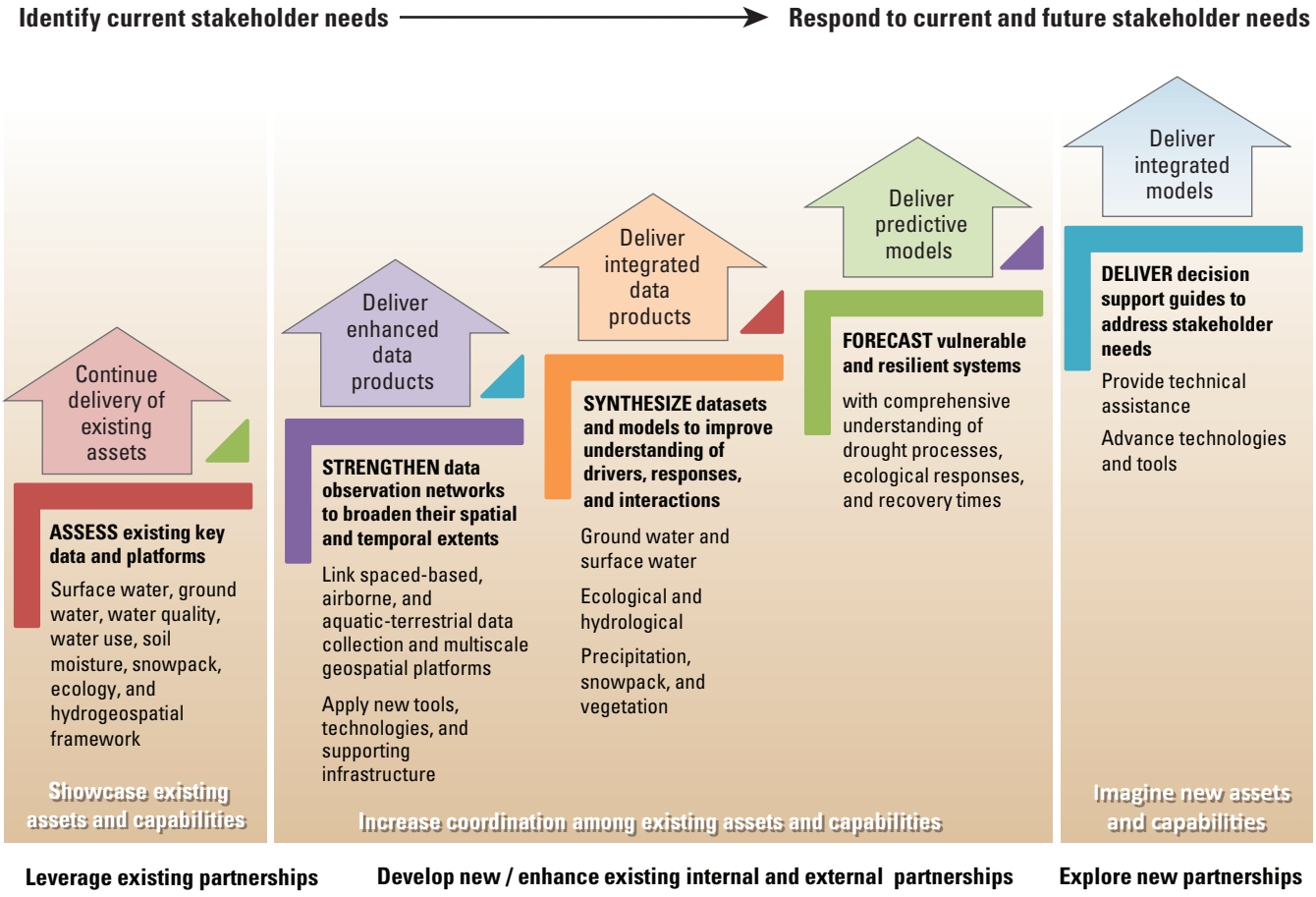


Figure 2. Conceptual diagram of steps needed to implement the USGS Integrated Drought Science Plan.

- Assessing key data and platforms,
- Strengthening observations across space and time,
- Synthesizing datasets and models,
- Forecasting vulnerable and resilient systems, and
- Delivering decision tools and services.

The first step of the USGS Integrated Drought Science Plan approach is to **ASSESS existing key data and platforms**. Many USGS data assets already are accessible and delivered to stakeholders. These include information about surface water, groundwater, water quality, water use, soil moisture, snowpack, ecology, and the supporting national hydro-geospatial framework. Existing internal and external partnerships were identified that are important to leverage in order to continue delivery of these data assets and support drought information needs.

Second, there is a need to **STRENGTHEN data observation networks to broaden their spatial and temporal extents** to effectively address stakeholders' questions not only in regions experiencing drought, but also to prepare other regions of the United States in anticipation of similar conditions. The USGS will develop new tools and technologies to expand and strengthen space-based, airborne, aquatic, and terrestrial data observation networks that collect information at multiple spatial scales. A sophisticated data-exchange, storage, and delivery infrastructure will be important to support this envisioned robust network.

Next, coordination of these strengthened data observations will enable researchers to **SYNTHESIZE datasets and models to improve understanding of drivers, responses, and interactions** of drought in new or enhanced ways. Improved understanding of the relationships between key data assets, both spatial and temporal, will provide the foundation for improved drought forecasting. Synthesis of groundwater and surface-water data and models, and hydrological, elevation, geological, meteorological, and ecological data are the key data integration needed. This approach, complemented by the use of a consistent hydro-geospatial framework, will improve transfer of science and knowledge across the Nation.

Last, once key datasets and models are synthesized and understanding of interactions improves, new comprehensive understanding of drought processes, ecological responses, and recovery times can be achieved. This will improve the ability to **FORECAST vulnerable and resilient systems**. These steps in the process, to strengthen, synthesize, and forecast, will require increased coordination among existing assets and capabilities, but are ultimately essential to build and **DELIVER decision-support guides to address stakeholder needs**. The new science and tools will help Federal, State, Tribal, and local resource managers who are seeking to identify vulnerable and resilient systems and improve planning and mitigation strategies.

Near-Term Opportunities

Deliver Integrated Products about Drought

Need: Increasing pressure on the Nation's water supply from drought is further complicated by the roles that more than 26 Federal agencies and many State, local entities, and Tribes have to collect, report, and synthesize water information. Improved access to water data and open exchange of water information is essential for understanding existing water resource issues and developing solutions for the future. As authorized in the SECURE Water Act (Public Law 111-11),

> "[T]he [DOI] Secretary shall conduct any appropriate activity to carry out an ongoing assessment of water use in hydrologic accounting units and major aquifer systems located in the United States, including the integration of any dataset maintained by any other federal or state agency into the dataset maintained by the Secretary."

The USGS is identified as the lead agency for the National Water Census.

To address challenges associated with delivering integrated products about drought, the Federal Geographic Data Committee and the Advisory Committee on Water Information launched the Open Water Data Initiative (OWDI) in summer 2014. The OWDI integrates distributed water information into a connected, national water data framework by leveraging existing systems, infrastructure, tools, modeling, data sharing, and solution development. The OWDI was initiated by DOI and managed by USGS in partnership with other agencies and organizations. Foundational geospatial datasets from USGS provide a strong basis for this integration. In 2016, the OWDI completed a pilot to link water data geospatially using the National Hydrography Dataset (NHD) through a Network Linked Data Index (NLDI). This enabled scientists and water managers to quickly query and compile water information from dozens of water agencies within a hydrologic network. Also in 2016, the USGS developed the HydroLink Tool, a Web-based geographic information system (GIS) application to aid researchers in linking observational data to the NHD datasets. This tool supports objectives of the OWDI and will be an essential step to synthesize ecological and hydrological data, but also can support any type of georeferenced point location data that has been observed on the landscape and would benefit from the added-value reference to these hydrology data assets.

Project goal and objectives: In order for scientists and water managers to use the full complement of drought-relevant water information, data need to be indexed to meaningful spatial units describing surface and groundwater hydrologic features. This can be accomplished by indexing Federal and other State and local water-use datasets, in cooperation with the Western States Water Council Water Data Exchange, to the hydrologic network using the NLDI. The information product could be built on the USGS National Water Census data resources and its Web-based services for sharing information, but targeted specifically at drought stakeholders. The completed pilot implementation of the NLDI mentioned above, includes a central Web-based catalog of stream linkages for a variety of water resources information, including water-quality monitoring sites, streamgages, and water-quality assessments, among others. The expansion of this effort would greatly benefit drought science work.

Some challenges must be overcome to achieve this goal. These include:

1. Developing methods for aggregating and anonymizing some water data while maintaining the foundational data's value to end users;

2. Linking water-use information to relevant hydrologic networks, aquifers, and among other water data products, such as water quality; and

3. Developing best practices for providing technical routines, protocols, and tools to identify and link water data to spatial units (such as census blocks and watersheds) for the water cycle using the NLDI.

The USGS has begun work on the High Resolution NHDPlus, which builds on earlier versions of the NHDPlus and collaborations with the EPA to enhance the resolution of nationally consistent surface-water representation from 3-dimensional elevation data.

Benefits: A common framework is essential for linking information among USGS programs concerning streamflow, groundwater, and water quality; climate and land use; ecosystems; and geospatial mapping. Expanding the catalog of data indexed to the national hydrologic network supports the development of consistent, accessible national models and their integration, important factors for increasing the value of models for decision-making.

Develop Integrated Ecohydrological Monitoring Networks to Assess Drought Impacts and Improve Conservation and Management

Need: There is a growing need to develop and implement innovative strategies to research, monitor, and manage freshwater resources as ecological and societal demands escalate simultaneously with climate-driven changes in water availability. While knowledge of how hydrological variability affects ecological and social processes is increasingly well resolved in large rivers, understanding of ecosystem services in headwater streams remains limited. However, headwater streams represent the vast majority of the Nation's waterways, and will be critical for maintenance of biodiversity, water availability, water quality, and ecosystem services under future drought. To help address these major data gaps, the USGS is uniquely positioned to develop and implement an integrated *ecohydrological research and monitoring network* that will advance understanding of drought effects and climatic resilience across aquatic, terrestrial, riparian, and wetland ecosystems. This integrated effort will advance coordinated USGS drought science and ultimately lead to development of a drought monitoring system and foster coordination for future response to drought issues nationwide.

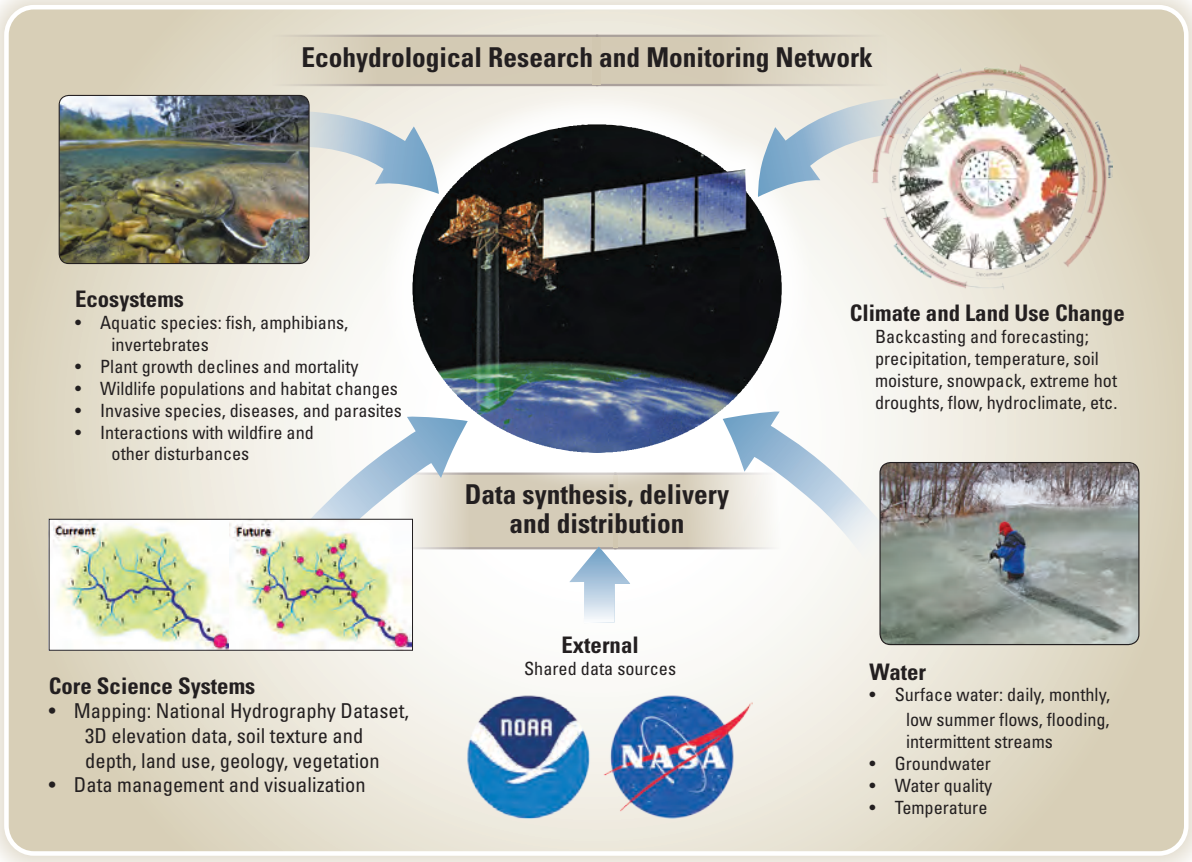


Figure 3. Ecohydrological research and monitoring network is an example integrated drought project concept.

Project goal and objectives: The overarching goal of this project is to integrate aquatic ecosystem research and drought monitoring throughout the entire range of aquatic environments especially where natural resource management and conservation is needed (fig. 3). The objectives of this study are to:

1. Develop cost-effective, novel methods for collecting ecohydrological data (e.g., drought severity, streamflow, water temperature, and biological parameters) across aquatic environments;
2. Design optimal strategies for investing in future monitoring and modeling; and
3. Link these efforts with other biological data to understand how drought affects ecosystems.

Benefits: This project will significantly improve understanding of ecological responses to drought and the ability of scientists to monitor and predict water availability at spatial scales important for aquatic species, such as invertebrates, fish, and amphibians; wildlife including beavers, mink, otters, wolves, and bears; and people. Moreover, remote-sensing data can be used to link direct effects of hydrological changes on riparian and upland vegetation and indirect effects on terrestrial species that use those habitats, such as beavers that play roles in storing and cooling water during periods of drought. Together, this coordinated and integrated project will enhance the capacity of the USGS in this interdisciplinary field while simultaneously benefiting natural resource decision-making, leveraging partnerships, informing policy, and addressing urgent stakeholder needs.

USGS Drought Online Resource and Communication

Providing effective communication to all stakeholders and partners has the potential to reach comparable levels of complexity as coordinating the science effort itself. As the first course of action, the USGS is developing a public Drought Website (http://www.usgs.gov/special-topic/drought) to bring together drought-related science information, products, tools, publications, and data for common access (fig. 4). The USGS Drought Website will present information in the areas of Data Collection and Integration, Modeling and Prediction, Drought Impacts, and Drought Resilience that compiles existing work from all USGS Mission Areas. To maintain continual access to new data, tools, and publications, the USGS will leverage existing systems that already are supporting USGS compliance with Federal open-data policies. A curated subset of publications from the USGS Publications Warehouse and released data from the USGS Science Data Catalog will be delivered through the USGS Drought Web page. In addition, as the USGS Integrated Drought Science Plan advances into implementation, status and progress also will be communicated through the USGS Drought Web page.

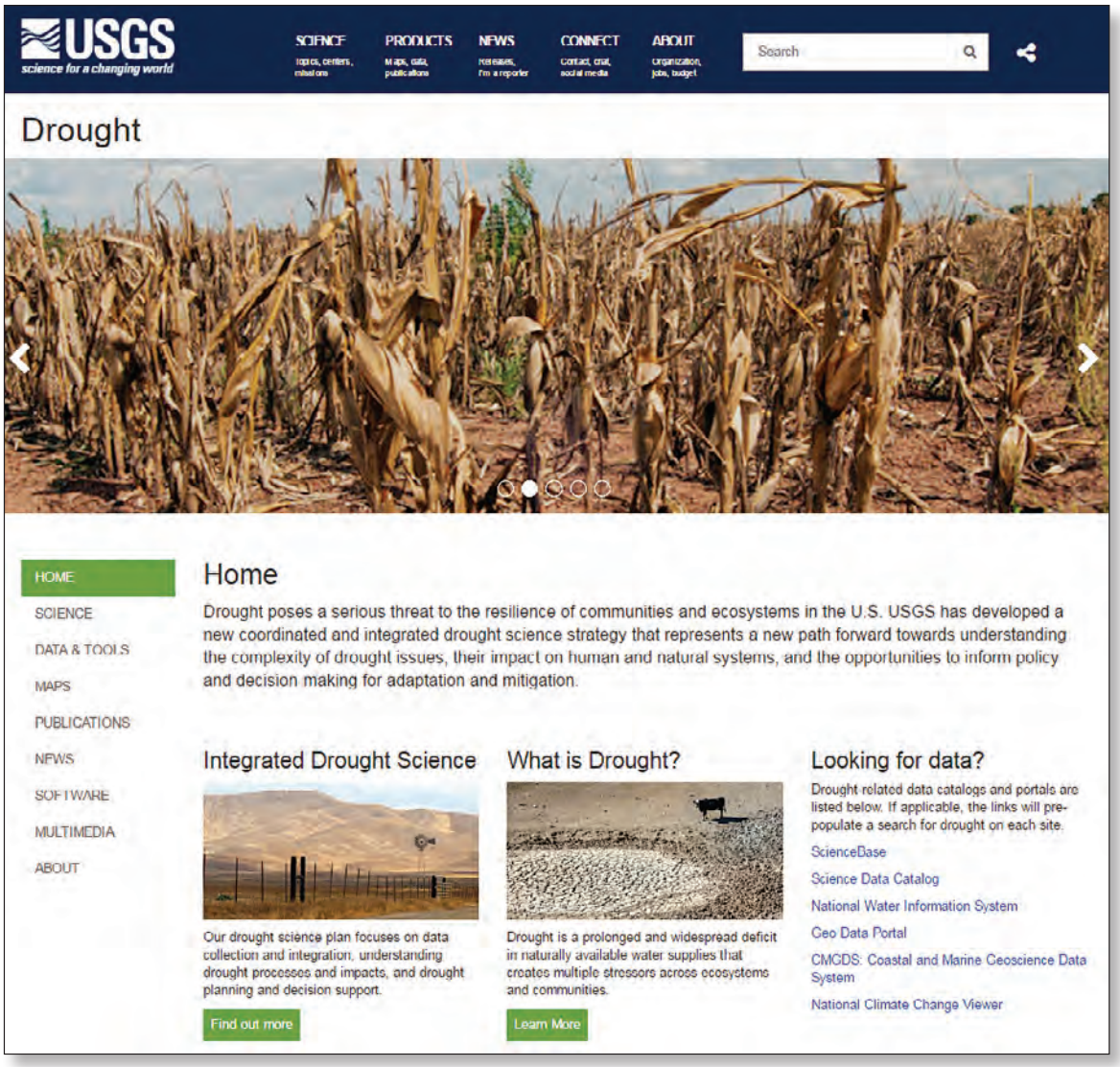


Figure 4. The USGS Drought Website provides a single location to find drought-related USGS products, tools and publications. https://www.usgs.gov/special-topic/drought/science-topics

Providing this common point of access for drought-related information, data, and tools will facilitate communication, collaboration, and coordination with stakeholders and partners at multiple levels of organizations. More specifically, the Website will be a resource between and among Federal, State, local, and Tribal stakeholders and partners while implementing actions in the NDRP's *Long-Term Drought Resilience Federal Action Plan*.

USGS Drought Partnerships and Coordination

The USGS Integrated Drought Science Plan lays out a general strategy for integrated USGS approaches to drought science. The overarching goals and implementation of the plan cannot, however, be completely realized without effective coordination of USGS capacities with the Federal agencies and State, Tribal, regional, and local partners that are supporting an enhanced understanding of drought.

The 2016 Presidential Memorandum: Building National Capabilities for Long-Term Drought Resilience (The White House, 2016) summarized the need for focused collaboration across all levels of government and the private sector as "critical to enable productive and workable solutions to build regional resilience to drought." The need for such focus crosses all objectives of the USGS Integrated Drought Science Plan. The authors of this prospectus have noted, for example, stakeholders' extreme need for monitoring efforts that characterize water supplies and support assessment of drought-risk. The in-place Federal water and climate data and analysis programs that help fill this information need, however, span across multiple agencies, including the National Aeronautics and Space Administration, Natural Resources Conservation Service, NOAA, National Weather Service, and the USGS. The need for coordination among these agencies, and their data programs, goes beyond ensuring data accessibility to include interagency awareness and coordinated design of critical hydrologic and ecologic monitoring networks. Similarly, many national and regional drought forecasting tools used by State, Tribal, regional, and local officials require input from multiple Federal agencies and programs. Improved coordination in the evolution of integrated decision-support tools will enhance the collective benefits of Federal programs to science and management partners.

The USGS has developed strong collaborative relationships with colleague agencies working in support of drought science, planning, and response. The USGS plays critical roles in regional and national interagency drought-related programs such as DOI's WaterSMART program and regional Climate Science Center partnerships, and the National Integrated Drought Information System. Increasing challenges associated with water management and drought resilience in the face of increasing water demand, however, add focus to the need to continue to evolve and improve coordination of Federal drought activities and communication with State and regional partners. To do this, the USGS will apply the same step-wise approach proposed for the integration of USGS drought science (fig. 2). As a first step, the USGS will **ASSESS** current coordination efforts, mechanisms, and practices in ongoing drought programs.

Defining who USGS works with and the effectiveness of those interactions will help to identify best practices and existing deficiencies. The Action Plan of the NDRP is useful for improving coordination among drought activities of Federal agencies. It also provides a context for guiding and coordinating Federal activities, including those of the USGS, with attention to local and regional priorities and needs. The USGS will use and extend the NDRP Federal Action Plan coordination framework to all drought activities, **STRENGTHEN** current coordination efforts, and establish new lines of communication and working relationships with engaged partners.

The goal of improving coordination of USGS drought science activities with other Federal agencies and State and local partners is a two-way proposition to deliver coordinated and integrated government drought science. The USGS will embrace and forward an "all in" philosophy for information sharing and will work toward strategic coordination and **SYNTHESIS** of Federal drought science activities. Delivered science will include model-based **FORECASTING** and mitigation tools for vulnerable and resilient systems. Products will be **DELIVERED** to all stakeholders who need them for decision support and to address general information needs of those present and active within affected landscapes. This coordination and communication focus will help minimize duplication of effort in Federal drought programs—instead allowing the USGS to build onto and integrate with long-standing and emerging drought initiatives led at Federal, State, Tribal, regional, and local levels.

A New Path Forward

Recognizing the critical importance of managing risk and improving resilience of our Nation's communities and ecosystems in the face of climate-induced drought, the **USGS Integrated Drought Science Plan** calls for coordinated and integrated USGS approaches to drought science. This new vision represents a new path towards understanding drought impacts on people and ecosystems and advancing critical information necessary for decision-makers to take action in the coming decades. The next step is to develop a future implementation strategy that identifies specific measures to implement this long-term vision across the United States. Ultimately, this coordinated and integrated approach will help our Nation prepare for and cope with drought to protect human health and safety, natural ecosystems, national security, our economy, and our quality of life in changing world.

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