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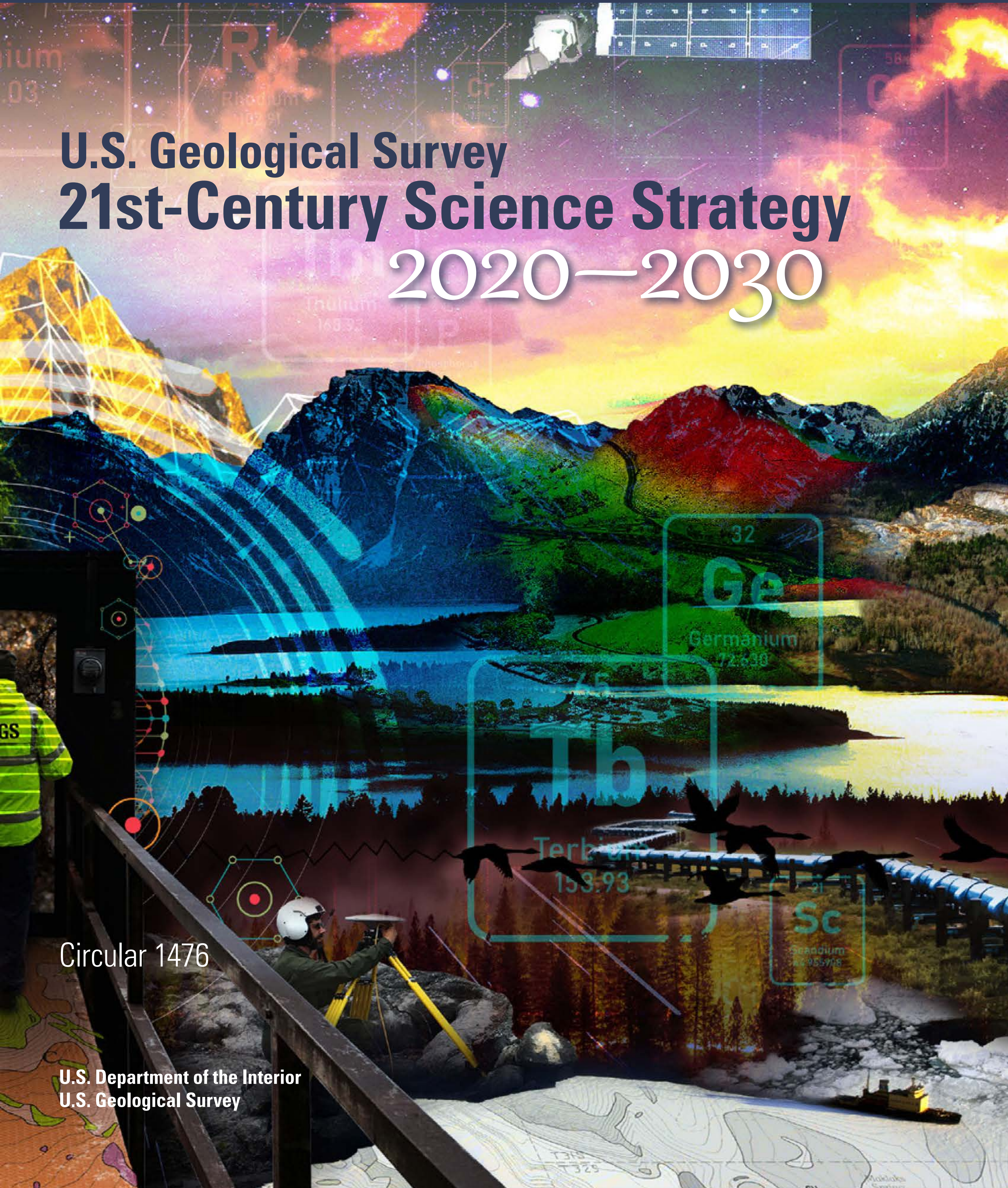
U.S. Geological Survey 21st-Century Science Strategy 2020–2030



Circular 1476

U.S. Department of the Interior
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Cover. Design by P.K. Cascio, U.S. Geological Survey.
Page i. View downriver of Powell Expedition boats on the Green River in Red Canyon, Utah, May 2019. Photograph by Anne Ballmann, U.S. Geological Survey.

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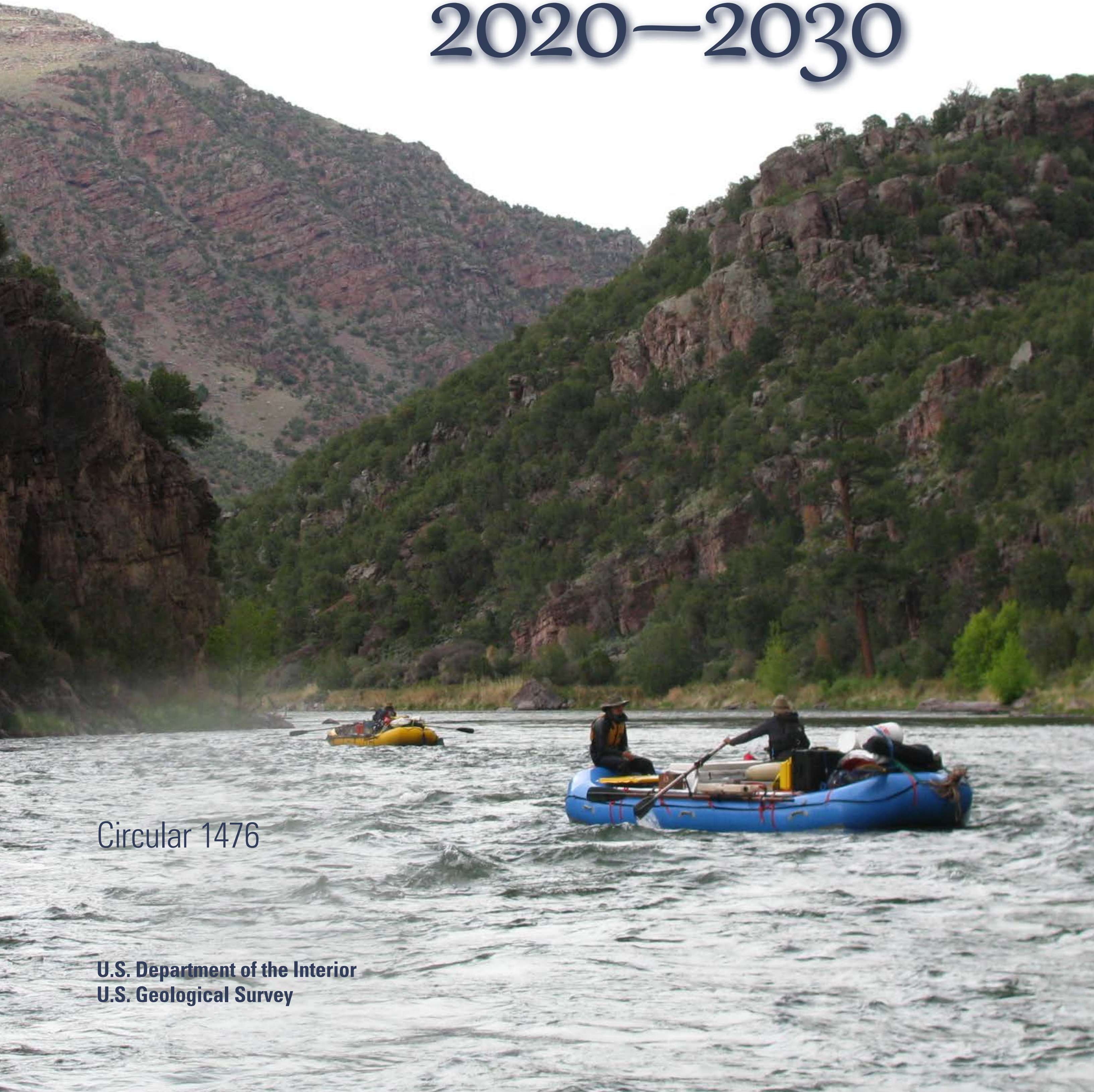

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U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2021

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Foreword

On the 75th anniversary of a report commissioned by President Franklin D. Roosevelt, Science the Endless Frontier, the Director of the White House Office of Science and Technology Policy, Kelvin Droegemeier, suggested that the United States is entering the second bold era of science and described the need for a new strategic framework as we enter the next era of science. This framework includes longer term planning horizons, cross-portfolio integration, and innovative partnerships among the "whole of the science community"—including private sector, academia, nonprofit organizations, and government—as well as inclusive research environments that lead to greater diversity.

For the U.S. Geological Survey (USGS) to play a vital role in this endeavor, we must engage in long-term planning. In 2020, we began the next major step in the evolution of the USGS's service to the Nation with an effort to further integrate the components of our science and information management and technology portfolios. Stewardship of the Nation's land, water, mineral, energy, and ecosystem resources involves weighing complex tradeoffs among multiple and often competing objectives. Increasingly in the 21st century, resource managers and decision makers need "the whole USGS"—integrated multidisciplinary data, research, geospatial tools, predictive models, and support tools—to inform their decisions.

"Now is the time to take stock of where USGS science will go in the next decade to ensure that we respond to 21st-century challenges with 21st-century science and technology."

The USGS is entering a new technological era with the potential to deliver transformational science. A revolution is underway in ground-, air-, and spaceborne sensors, and access to expanding crowd-sourced data can provide essential information about the Earth and its systems at unprecedented spatial and temporal resolutions. On-demand storage, processing hardware, and software are changing the paradigm for scientific computing and analysis, allowing the Earth System Science community to take advantage of the age of big data and cloud computing. The historical and real-time data streams and targeted research for which we are known will be paired with the ongoing explosion in information management and technology capabilities to catalyze new types of analysis and enhance our knowledge.

Now is the time to take stock of where USGS science will go in the next decade to ensure that we respond to 21st-century challenges with 21st-century science and technology. This 21st-century USGS strategy and vision for the decade 2020–2030 embraces an integrated and predictive capability that accounts for complex natural system interactions, anticipates the likelihood and consequences of evolving threats and hazards, and helps guide resilient adaptation and mitigation efforts. The USGS will step boldly into the next few decades by delivering advanced science products to further our Nation's prosperity and ensure our citizens' safety and well-being.

This strategy lays out a path for the next evolution of USGS science including a new integrative, predictive capability called EarthMAP that takes advantage of the USGS's strengths, our expertise spanning the full range of Earth and biological sciences, our "boots on the ground" presence, and our national and international scope and responsibilities. We will continue to work across disciplines to innovate scientific data collection and interpretation that provide essential inputs to EarthMAP and ways to test and improve the effectiveness of our predictive modeling. EarthMAP will incorporate advances in sensor technologies, integrated modeling, artificial intelligence, machine learning, cloud computing, and high-performance computing in order to observe, understand, and predict change across spatial and temporal scales in real time and over the long term.

Enhanced integrative capabilities and technology will be necessary to answer the increasingly complex, interdisciplinary, and computationally intensive scientific questions that are most important to the Nation and the world. Recognizing and embracing this new paradigm presents tremendous opportunities for the USGS to lead the Earth and biological science community in the decades to come and to contribute to a holistic understanding of our Earth as a system of systems. Our future success will be determined by the decisions and investments we make in our people, technology, and scientific research in the coming years.

These are exciting times and opportunities!

James F. Reilly II
Director

Bryce Canyon and Grand Staircase-Escalante, Utah. Photograph by Alex Demas, USGS.

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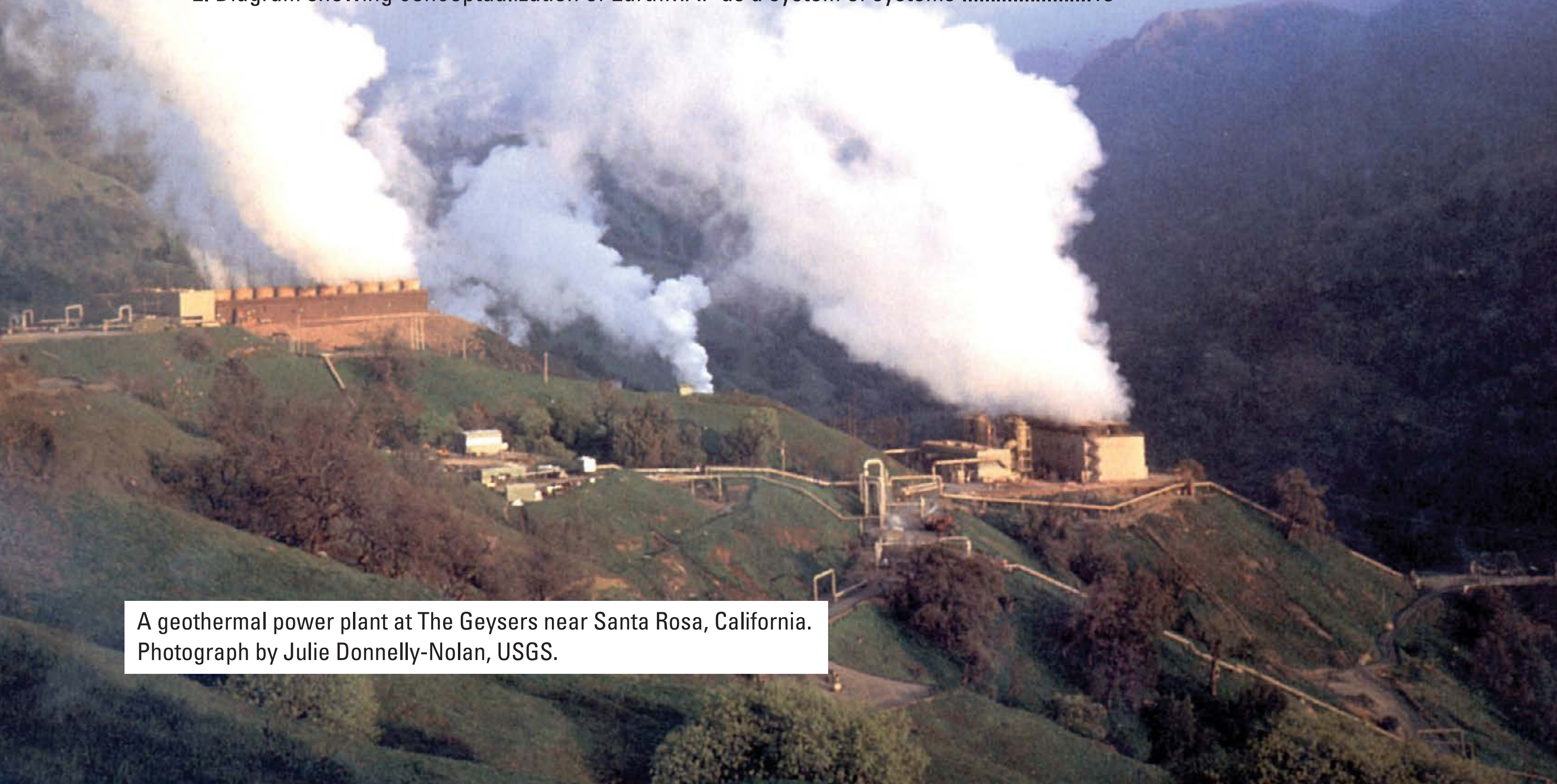


A geothermal power plant at The Geysers near Santa Rosa, California. Photograph by Julie Donnelly-Nolan, USGS.

Forster's tern chick in a nest in Pond A16, Don Edwards San Francisco Bay National Wildlife Refuge, July 2019. Photograph by Jeanne Fasan, USGS.

U.S. Geological Survey 21st-Century Science Strategy 2020–2030

Introduction

Since 1879, the U.S. Geological Survey (USGS) has been the Nation's primary Federal source of non-regulatory, non-advocacy scientific information about the Earth and its processes. Created by an act of Congress, the USGS has evolved over the ensuing 142 years, matching its talent and knowledge to the needs of society and the progress of science and technology in order to accomplish its mission.

Today's Earth system challenges are far more complex and urgent than those that existed in 1879. Society's greatest challenges are directly or indirectly linked to major areas of USGS science. Increased pressures on natural resources continue with consequences for national security, food and water availability, natural disasters, human health, and biodiversity loss. As we look forward 10, 20, and 30 years, our mission will be more important than ever before. A broad but coherent view is required for stewardship of the Nation's land, water, mineral, energy, and ecosystem resources, which involves complex tradeoffs among multiple, often competing objectives. Increasingly, resource managers and decision makers need "the whole USGS": integrated multidisciplinary Earth and biological science data, geospatial tools, predictive models, decision-support tools, and the expertise to interpret them.

Topographic and geologic mapping conducted by Major John Wesley Powell and crew during the 1869 Green and Colorado Rivers expedition was accomplished with compasses, sextants, chronometers, mercury barometers, and thermometers (USGS, 2019). Modern mapping is aided by digital imagery, pulsed-laser light detection and ranging (lidar), and geophysical data acquired from satellites, aircraft, and unmanned airborne systems. Geologic and topographic data can be processed through computer software to produce 3D models and illustrations. The geologic map of the future may be a fly-through, virtual-reality experience that will allow us to understand the architecture of the Earth as never before.

As with any scientific endeavor, new technology allows us to better refine what we know about the way the world works. Molecular methods allow environmental DNA (eDNA) to be detected, sampled, and monitored. The application of eDNA is boundless. Examples include early detection and mapping of aquatic invasive species, distribution and abundance of species, and detection of pathogens or diseases and their transmission to and from wildlife.

Our future vision and success will be determined by the decisions and investments we make in our people, technology, and partnerships in the coming years. This USGS Science Strategy endeavors to define the next evolution of USGS science, laying out a path for the next decade of innovation and achievement in service to society.

Photograph of Earth from the Blue Marble collection, National Aeronautics and Space Administration.

USGS Mission and Vision

USGS science advances the economic welfare of the Nation, protects the safety and health of our people, contributes maps and data to the public good, and advances understanding of the environment, ecosystems, and species that share our planet. Although the science mission of the USGS is broad, its elements are intrinsically related. Water, energy and mineral resources, ecosystems, natural hazards, and land use interact in myriad ways, often with complex and unanticipated consequences. Through collaboration with partners in government, academia, industry, and beyond, USGS science addresses enduring societal needs

Simply stated:

The USGS mission is to monitor, analyze, and predict current and evolving dynamics of complex human and natural Earth system interactions and to deliver actionable intelligence at scales and timeframes relevant to decision makers.

The USGS is committed to an unbiased and impartial scientific understanding of the Earth's systems and to continually evolve as societal needs change while embracing new technologies and capabilities.

Our vision is to

Lead the Nation in 21st-century integrated research, assessments, and prediction of natural resources and processes to meet society's needs.

Challenge and Opportunity in the 21st Century

The Nation faces unprecedented challenges: increasing demand for energy and mineral resources, changing land resources, vulnerability to natural hazards, water security and availability, emerging diseases affecting wildlife and human health, and loss of critical or unique ecosystems. These challenges occur in a context of broad environmental, technological, and societal change, all of which shape our long-term vision and direction which demand greater integration of our scientific capabilities and information management technologies. Such times of change also provide unprecedented opportunities for innovation and science to support the Nation in addressing challenges.

The Earth System Challenge

Thriving societies around the world have developed with a reliance on stable functioning of the Earth system. However, this complex suite of interlinked physical, chemical, biological, and human processes and systems is exhibiting increased risk of destabilizing change that could have profound societal impacts. Of a set of metrics describing nine highly interdependent processes and systems that help regulate the stability and resilience of the Earth system, changes observed in four are thought to have already exceeded threshold (potentially destabilizing) levels at the planetary scale (Steffen and others, 2015):

- Climate change (metrics: atmospheric carbon dioxide and increases in top-of-atmosphere radiative forcing);
- Change in biosphere integrity (metrics: biodiversity loss and species extinction);
- Biogeochemical flows (metrics: phosphorous and nitrogen loadings); and
- Land system change (metrics: amount and pattern of change in all terrestrial biomes, and biogeophysical processes in land systems that directly regulate climate through exchanges of energy, water, and momentum).

Other processes and systems, including the water cycle (metrics: freshwater availability and use) and the introduction of novel entities that exhibit persistence and mobility (metrics: organic pollutants, radioactive particles, microplastics, and nanoparticles), have not reached threshold levels at the planetary scale but pose substantial risks at regional and local scales. The potential impacts of these issues, and the uncertainty surrounding them, complicate the already challenging tasks of exploring and managing natural resources, supplying food and shelter, and mitigating the effects of natural hazards, all of which are essential for a society to thrive. Decision makers—resource managers, emergency managers, and policymakers—are faced with a more complex range of issues than in the past, as well as a vastly increased body of potentially useful information to interpret. They need rapid and timely access to reliable information that addresses their specific problems. They need actionable intelligence to make informed decisions that may ultimately guide the sustainability of the planet. Actionable intelligence is scientific information that is directly available for use by stakeholders and enables decision makers to take appropriate and timely action (without having to go through an additional production or interpretive phase).

Paramount to helping society address these risks and plan for potential change is developing a more complete and integrated understanding of the complexity of these interdependent processes and systems, the capacity to predict their behavior, and the delivery of actionable intelligence to decision makers. This is the heart of the USGS mission and vision for the 21st century.

The past several decades yielded a steady advance of the stature and capabilities of a broad spectrum of physical, chemical, and biological scientific disciplines and subdisciplines, enabling an unprecedented understanding of numerous processes within the Earth system. Moreover, an increasing recognition of the need to connect and integrate this understanding across disciplines has fueled exploration of the intersections between disciplines, consistently providing new insights, new understanding, and new capabilities. With growing scientific and societal awareness of the profound challenges previously noted, these disciplines have been evolving towards the consideration of the Earth as a single, unified system. Earth System Science (ESS) is a rapidly emerging transdisciplinary effort aimed at building a unified understanding of the structure and function of the Earth as a complex, adaptive system (Steffen and others, 2020). Three interdependent foci drive ESS forward: (1) observations of the Earth system, (2) computer simulations of system dynamics into the future, and (3) high-level assessments and syntheses that initiate the development of new concepts.

The USGS, long at the forefront of disciplinary and interdisciplinary advances within the biogeophysical sciences, has a significant opportunity to accelerate the evolution of a unified understanding and prediction capability for the Earth system across multiple spatial and temporal scales. Initially focused on the oceans and atmosphere, with only simplified land processes, ESS has evolved with a clear recognition of the need for a more robust treatment of terrestrial processes and functions—physical, biological, and chemical—and their interactions with broader planetary systems. The USGS is uniquely positioned to assist and lead in this effort over the next decade. Doing so will require transdisciplinary integration and advancement of (1) our data acquisition and management, (2) our modeling and prediction capabilities, and (3) our delivery of actionable intelligence. Moreover, these three foci will be supported with broad and aggressive characterization of biogeophysical processes, strategically leveraging state-of-the-art technologies to sustain and support the science (fig. 1). The USGS will establish enterprise information management and technology (IMT) capabilities that the Bureau workforce can leverage at multiple scales with consistent interoperable software and database solutions to better facilitate integrated work. Investing in IMT infrastructure is fundamental to strengthening the backbone for conducting science. We will do all of this in concert with a broad community already working to advance ESS. To accomplish this, we will work in unison, as a whole organization, focused on this challenge.

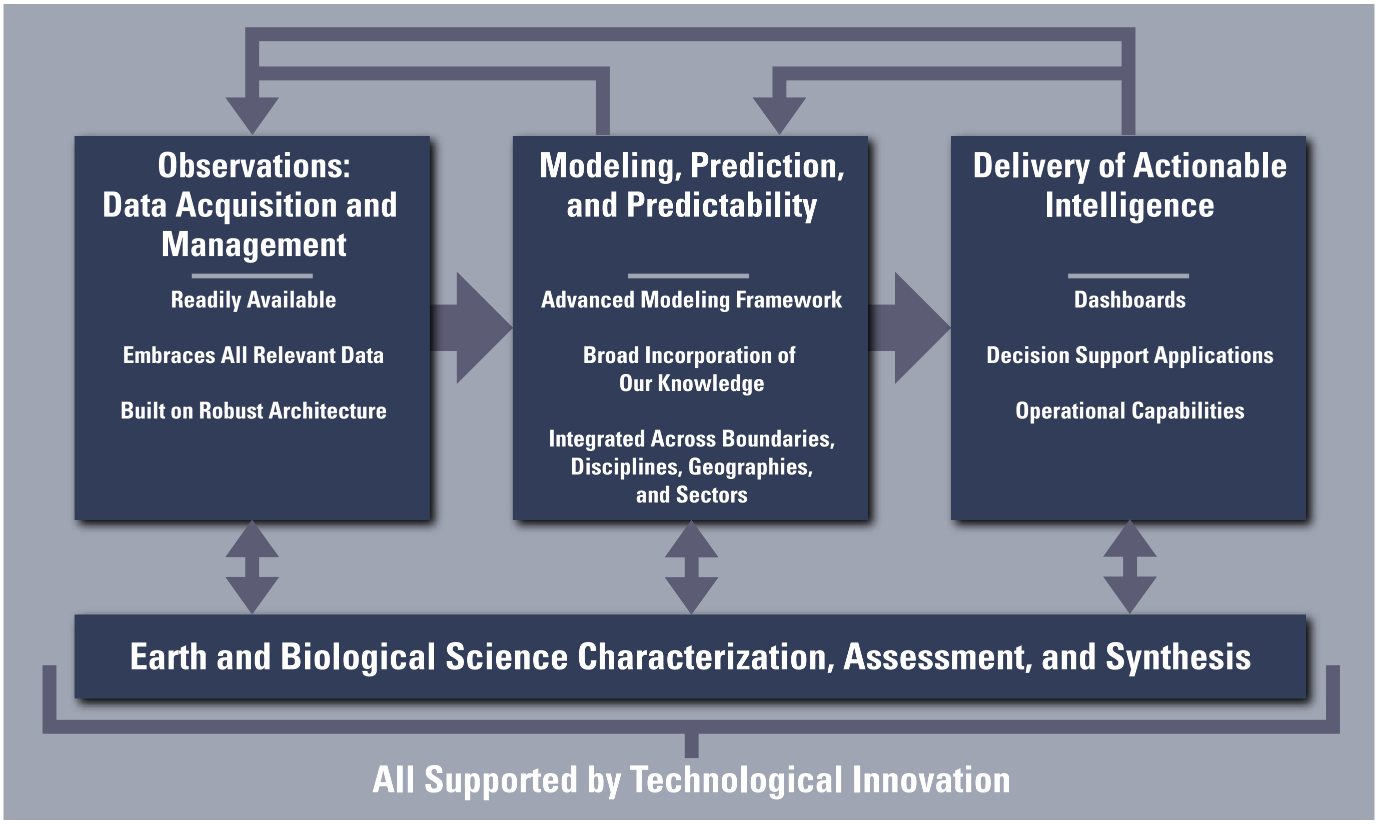


Figure 1. Three interdependent foci—data, models, and delivery of actionable intelligence—must be underpinned by science to understand, characterize, and synthesize system processes. All must be supported by state-of-the-art technologies. Each of these components drives requirements for the others and must be integrated and advanced together for the USGS to address societal challenges in the 21st century.

Observations: Data Acquisition and Management

Observations underpin the scientific process and are crucial to developing understanding of a unified Earth system. The Earth and biological sciences generally lack sufficient observational data at national scales. To address the Earth system challenge, the USGS will innovate to embrace all relevant data, both quantitative and qualitative, regardless of source, and extract as much meaningful information from them as possible. Making full use of all relevant data—historical and contemporary—is fundamentally necessary to establish benchmarks for change, to reduce uncertainty, to calibrate and validate models, to train machines to search for patterns and relations, and to accomplish a myriad of other purposes. Over the next decade, the USGS will adopt an aggressive stance towards the acquisition and full use of all relevant data, strengthening our research and development capabilities to enhance usability of data (U.S. Group on Earth Observations Subcommittee, Committee on the Environment of the National Science and Technology Council, 2019).

Data originating from within the USGS range from a few observations at a small plot scale, to national monitoring networks, to global satellite observations, to long-term records of physical, hydrological, chemical, and biological observations. These observations over small spatial and temporal scales provide valuable insights into process dynamics but are often challenged by heterogeneity and thus can be difficult to scale (Acocella, 2015). Earth observing satellites such as Landsat provide consistent, repeated observations globally, but sensor and platform limitations constrain what we are able to observe and when. Over the next decade, the USGS will work to develop systematic frameworks to link our observational capabilities. Part of this will require strategic modeling to bridge scales, but much will depend on more deliberate, integrative design of our observing systems and monitoring networks to fill critical gaps in what is observed, where, and how often. The USGS will take a concerted approach towards a more holistic observational data acquisition paradigm.

Crews make visual observations of activity at fissure 8, Kīlauea Volcano, Hawaii, May 31, 2018. Photograph by USGS.

Sensors play a growing role in acquiring data at their source. The Internet of Things (IoT) is a system of internet-connected physical objects (for example, vehicles, monitoring equipment, smart appliances, light bulbs, and fixtures) that collect and transfer data over a network using sensors and machines without human intervention. Processing data at the originating source and integrating that data collection with other computing elements automates data transfer and related actions into an IoT model. The USGS will plan and execute a secure, integrative approach to data acquisition and monitoring while leveraging artificial intelligence (AI) computing and machine learning (ML) capabilities to increase the rate by which data can be interpreted and turned into knowledge. This will accelerate phases of our scientific project life cycle.

Our approach will fully engage the broader ESS community to make all USGS data more broadly available to others and to acquire relevant observational data from others to advance our science (U.S. Group on Earth Observations Subcommittee, Committee on the Environment of the National Science and Technology Council, 2019). USGS research will link our extensive and intensive datasets with airborne- and satellite-based remote sensing observations to improve process understanding. Towards that end, the USGS has opportunities to be more aggressive in leading strategic large-scale interdisciplinary observational campaigns and field experiments that expand and broaden our understanding of Earth processes.

A more aggressive stance towards the use of multidisciplinary observational data establishes the requirement for more effective data management. The USGS's ability to elevate and accelerate a comprehensive interdisciplinary understanding of the Earth rests upon unifying and strengthening our data collection methods and protocols, our data systems and architectures, and accessibility of our data. Over the next decade, the USGS will develop and implement robust infrastructures for collection, curation, and dissemination of data. Enterprise architectures, common data vocabularies, and effective metadata ontologies are needed across USGS to support emerging as well as traditional data, to enable rapid and seamless discovery of relevant data, and to support highly structured data needs such as those required by modeling and decision analysis systems.

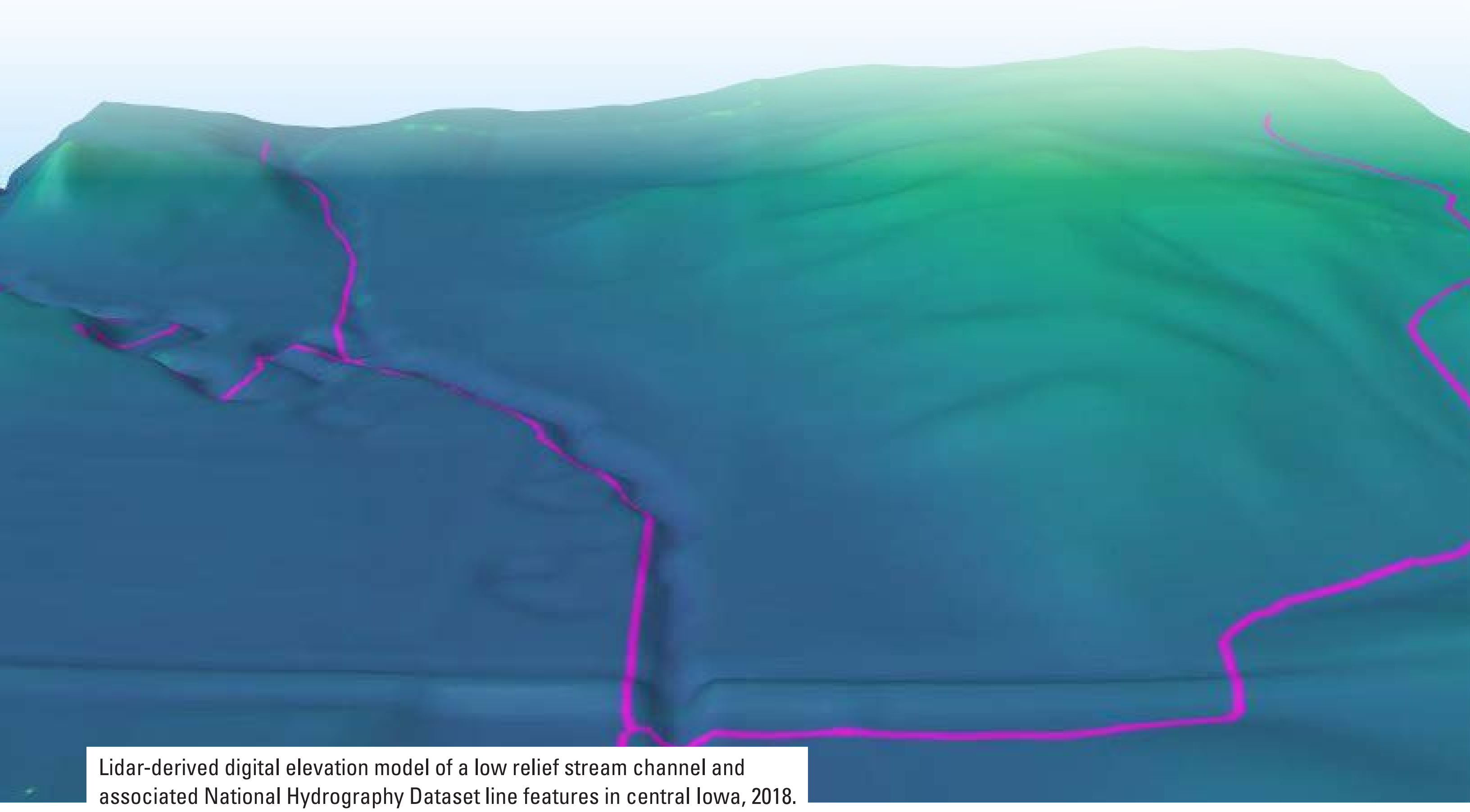
Fire monitoring during wildfires, Santa Fe National Forest, New Mexico, 2014. Photograph by Rachel Loehman, USGS.

Modeling, Prediction, and Predictability

Models integrate our understanding of processes and system dynamics within a consistent framework which can then be used to test our understanding, make predictions, and generate new hypotheses. Hundreds of existing USGS models describe terrestrial processes and subsystems and range from simple heuristics to detailed algorithmic representations of complex process interactions. Each of these models improves our understanding of some portion of the Earth system and receives some form of validation and testing. Some models are predictive, and some lead to new ideas and hypotheses. Continued development of models at the process-oriented, subsystem level within the USGS is necessary for the growth of our fundamental understanding of the Earth's components; however, the grand challenge and opportunity for the USGS is to go further by integrating these process and subsystem components into broader system frameworks. Over the next decade, the USGS will incorporate and link our models within a rapidly evolving next generation of Earth system simulation and prediction.

Numerical models began decades ago as simplistic conceptualizations of major, first-order Earth system dynamics, and they have steadily evolved into robust general circulation models, global and regional climate models, and numerical weather models. In parallel, comparable models have evolved that describe a broad range of hydrological, biogeochemical, biological, and ecological processes and subsystems. The completeness of process representations largely depended on the principal purpose of the model and was often constrained by the availability of data and computational capacity. More recently, the interdependent nature of all Earth system processes, increased data availability, and increased computational capacity have driven the emergence of Earth System Models (ESM)s that incorporate a comprehensive range of rigorous physical, chemical, and biological processes and feedback mechanisms to achieve improvements in skill and utility.

Central to the development of ESMs is the recognition that, at timescales ranging from sub-seasonal to seasonal (2 weeks to 12 months) to decadal, many facets of terrestrial biogeophysical processes have a greater influence on system predictability than the comparatively transient troposphere. For example, in humid regions, feedbacks associated with the biosphere response to radiation and water availability explain as much as 30 percent of the variance in moist convection leading to precipitation (Green and others, 2017). Omitting or oversimplifying such processes can be severely detrimental to prediction skill. Still relatively nascent, ESMs are developing rapidly to address challenges in understanding and predicting the Earth system. Consequently, more and more biogeochemical and ecosystem functions are being incorporated into ESMs. A broad suite of USGS expertise is highly relevant to this effort.



Lidar-derived digital elevation model of a low relief stream channel and associated National Hydrography Dataset line features in central Iowa, 2018.

Key opportunities for the USGS to play a significant leadership role in the evolution of ESMs include the following:

- Integrating current understanding and modeling capabilities through advanced model representations and architectures that link interdisciplinary processes, as well as their errors and uncertainties, to identify strengths and weaknesses and gain new insights into interdependencies;
- Bringing expertise to bear on the problem of advancing and optimizing appropriate representation of terrestrial physical, chemical, and biological processes within ESMs, through hypothesis-driven contribution of new process representations and through engagement in ESM data assimilation, calibration, and validation activities (National Academies of Sciences, Engineering, and Medicine, 2016; Bonan and Doney, 2018);
- Expanding the capacity to incorporate human dynamics and anthropogenic influences—including behavior and decision making that can alter system dynamics—into the biogeophysical modeling realm (Müller-Hansen and others, 2017);
- Advancing understanding of the limits to predictability within the terrestrial Earth system and prioritizing development of additional process components that are most important to improve prediction skill (Vought and Droegemeier, 2019);
- Conducting model sensitivity studies such as Observing System Simulation Experiments to inform the design of our data networks to improve modeling skill (National Academies of Sciences, Engineering, and Medicine, 2016);
- Enhancing USGS technological skills to support the high computational, storage, and networking demands of working in the ESM realm, including long-term investment in computer scientists, software engineers, applied mathematicians, and statistics researchers necessary to complement our biogeophysical science expertise (National Academies of Sciences, Engineering, and Medicine, 2016);
- Advancing opportunities in high-performance computing (HPC), cloud computing, and the ability to seamlessly traverse both on-premise and cloud infrastructure as one environment, transparent to the user;
- Preparing existing USGS data and associated knowledge to be used in ESM parameterization and validation;
- Establishing robust Bureau-wide developmental testbed infrastructure, including technology, methods, procedures, and policies needed to establish evidence-driven approaches to regularly and systematically advance USGS ESM capabilities; and
- Advancing USGS software and application development activities to include more opportunities to leverage ML, infrastructure as code, and big data collaboration.

A USGS scientist surveys Global Positioning System ground control point locations on North Topsail Beach and within the Camp Lejeune Marine Corps Base, North Carolina, July 2020. Photograph by Chelsea Stalk, USGS.

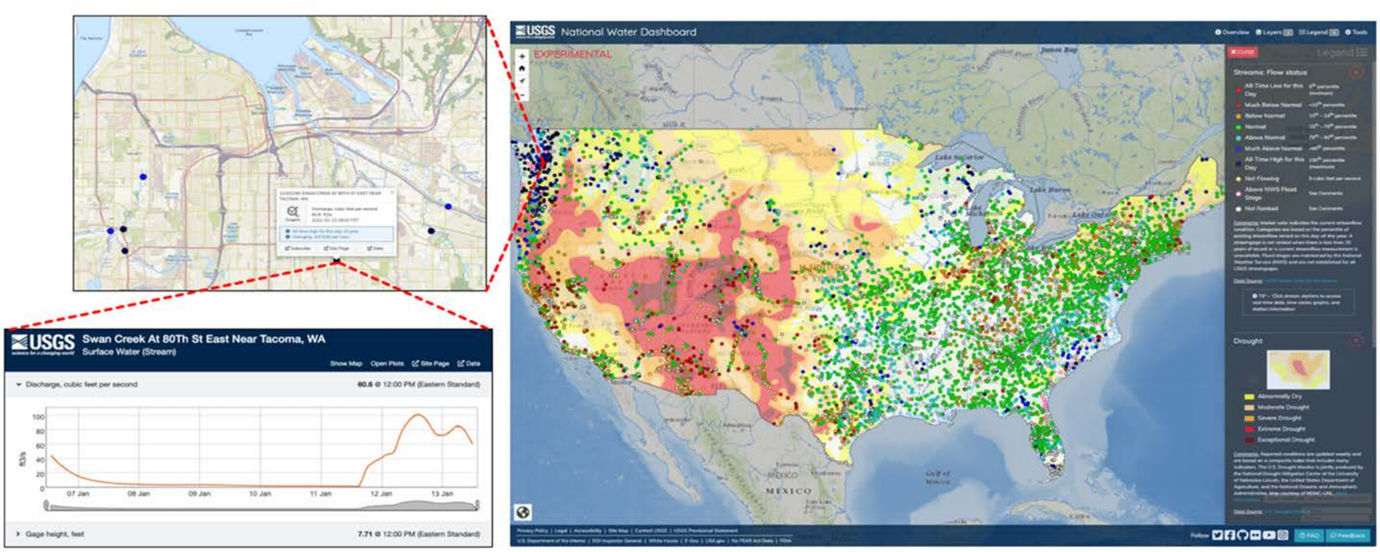
Delivery of Actionable Intelligence

Central to the USGS vision and mission is meeting society's needs through the delivery of information at scales, at timeframes, and in forms relevant to decision makers. The actionable intelligence concept requires understanding of the fact that decision makers frequently lack resources (for example, time, expertise, or infrastructure) to digest, interpret, manipulate, or otherwise work to transform the information they receive into something they can use. To be most useful and relevant to stakeholders, the USGS must strive to answer their questions specifically, succinctly, and simply, despite the fact that their questions may be quite complex and may require extensive research and analysis to answer. Moreover, our information must be timely. It is equally important to understand which factors drive the timing of a decision; when that time comes, decision makers will proceed with the best information they have. Information delivered after a decision has been made has low utility. Provision of USGS information "at the speed of decision making" means that in many cases the USGS must anticipate what will be needed and begin developing it in advance. This in turn places a high emphasis on early stakeholder engagement to understand and anticipate their future needs and on developing predictive capabilities that provide information in advance of when it is needed.

Timely delivery of actionable intelligence is dependent upon the integration of data and modeling. Tools such as dashboards and decision-support applications provide excellent mechanisms to synthesize diverse sources of information and visualize the results in effective ways. These tools can be tailored to specific needs much faster when the underlying data and information are readily accessible, well organized, and in compliance with standards supported by such tools. The USGS actively develops these types of tools and has many opportunities to streamline these efforts, as well as to make the tools more consistent in appearance to better establish the USGS "brand" which would simplify the learning process for stakeholders encountering each new tool. Seizing these opportunities will make it easier to meet the goals of actionable intelligence. Accelerating information delivery means we must give careful consideration to how our Fundamental Science Practices and review processes can keep pace.

Developing broader operational capabilities throughout the USGS will be an important approach towards timely delivery of actionable intelligence. For example, the routine operational delivery of provisional data in near real time gives decision makers something they can use immediately. The USGS has many opportunities to move more of its data into operational frameworks. Similarly, as the USGS moves into the realm of predictive ESMs, there will be increasing opportunities to provide model output as standard operational products, again giving decision makers actionable intelligence, with opportunities for later refinement. By delivering such products routinely, the USGS can become a consistent, reliable link in decision-making "supply chains," fostering advocacy for the continuation and growth of USGS products and services.

Pursuing these opportunities will require the USGS to place more focus in the next decade on all aspects of data science, but especially on communication aspects with visualization, cognition, and decision-making tools. Understanding how USGS information is perceived and used by decision makers will be a key factor in making our information more actionable. Small differences in something as simple as a color scheme, which is well understood in areas such as cartography, can have a significant influence on how a product is interpreted and thus how effective it is. As the USGS broadens its portfolio of 21st-century products and services, more expertise will be needed in this area to ensure maximum effectiveness.



The USGS National Water Dashboard (https://dashboard.waterdata.usgs.gov/) provides provisional real-time data collected at USGS stations in context with weather-related data from other public sources.

Earth and Biological Science Characterization, Assessment, and Synthesis

The three foci discussed previously must be supported by a strong scientific foundation. The scientists within the USGS provide understanding of the causes, effects, distributions, relations, and impacts of fundamental processes and system dynamics throughout the biosphere, hydrosphere, lithosphere, cryosphere, and atmosphere. Characterization and interpretation of natural hazards, water resources, animal health, invasive species, energy and mineral resources, and topography and terrain are essential for the continued success of the USGS and for acquiring the advanced understanding needed to develop an integrated, systems view of the Earth. Among other benefits, such characterizations provide a critical baseline for measuring future change. Our strength has been and will remain our disciplinary expertise, but going forward will require acquiring additional capabilities to build and synthesize a more comprehensive Earth system understanding.

Hazard risk and vulnerability assessments, as well as post-event characterization, are invaluable to helping the USGS communicate risk and inform decision making. Such assessments, together with related monitoring and research activities, provide a proven foundation for the USGS to build upon to inform broader Earth system challenges in the 21st century. USGS approaches to monitoring earthquake, volcano, and flood hazards and warning the public about them are good working examples of delivering timely, actionable intelligence in an operational style and can serve as models or prototypes for future development and expansion. Moreover, understanding how these local and regional risks compound with broader Earth system risks is critical for assisting decision makers to assess their overall risk profile and to develop effective mitigation strategies.

Despite the intrinsic importance of the water cycle in the functioning of Earth's interdependent systems, we still have only rudimentary knowledge of the quantity, quality, and distribution of water resources across the Nation. Stream reaches outnumber streamgages by four orders of magnitude. Only about 1,000 sites routinely measure snow water equivalent, and only about 1,000 groundwater monitoring sites report data in real time. The vast majority of ponds, lakes, and reservoirs have no commonly reported measurements. USGS opportunities for more comprehensive assessment of water resource availability depend heavily on harnessing all available data and combining those data effectively with models to fill observational gaps. Data assimilation and new technologies such as using AI to augment and learn from the modeling process will play increasingly important roles in the next decade.

Characterization of the distribution, dynamics, and severity of biological threats and how these threats respond to environmental factors is paramount to reducing the occurrence of wildlife disease and invasive species and the extensive costs these incur. With the emergence of new sensor technologies and a greater focus on integrating our observing systems and data management systems within the USGS, we have exciting opportunities to establish innovative surveillance systems for early detection of biothreats and to improve assessment and prediction of their extent and effects. Improved early detection combined with better understanding of underlying environmental factors may create new opportunities to identify signals of broader Earth system change that otherwise might go undetected.

The USGS conducts new assessments of energy and mineral resources in basins across the globe, expands existing assessments by using new sensing and exploration technologies, improves mapping of the surface and subsurface, and evaluates future energy and mineral resources ranging from geothermal energy and heating resources to potential mineral resources in mining and other waste products. The USGS can help ensure the Nation can meet its resource needs sustainably by characterizing the full life cycle of energy and mineral resources with an integrated, interdisciplinary perspective that provides a more complete understanding of the feedbacks among energy, mineral, and other resource development. Moreover, this approach creates an opportunity for the USGS to represent this improved understanding within ESM frameworks to explore broader system interdependencies and feedback.

Characterization and mapping of the Earth's surface and subsurface composition and structure are foundational to the USGS mission. Expanding, enhancing, and integrating our 3D-elevation datasets, hydrography and hydrographic mapping products, geologic mapping, and land imaging will enable innumerable opportunities throughout the USGS and beyond. Because the fundamental interdependencies among physical, chemical, and biological processes often occur at small spatial scales, increasing the spatial resolution of observations, terrain data, and models to resolve and parameterize these processes has been a key factor in improving understanding of the Earth system. Continuation of ongoing USGS efforts in this arena will fuel advancements in ESMs for many years to come. The USGS has unique and important opportunities to exploit the long temporal record of high-resolution Landsat data to explore land surface change and relate that to change in process dynamics through advanced modeling and analytics. Improved hyper-resolution elevation and hydrographic data create many new possibilities for hydro-ecological and biogeochemical modeling at fundamental process scales, with greater potential to scale up consistently to watershed, regional, and national scales. Development of a seamless national geologic map will enhance energy and mineral production, hazards mitigation, groundwater resource management, infrastructure development, and more. In this way, the USGS can build upon its long history of mapping our Nation and planet by continuing to advance the technology and understanding needed to meet society's needs.

Technological Innovation

To pursue the necessary improvements in data acquisition and management, modeling and prediction, and provision of actionable intelligence, and to maintain and strengthen our characterization, assessment, and synthesis of fundamental processes and systems, the USGS will need to make the most of available and emerging technologies that enable USGS science. These technological innovations will be implemented with a continued emphasis on cybersecurity to ensure the integrity and availability of the data for our scientists and partners.

The Nation's natural resource challenges coincide with an era of unprecedented innovation and technical change that is occurring faster, more efficiently, and with greater accessibility than ever before. Rapid advances in AI/ML, augmented and virtual reality, blockchain, IoT, robotics, autonomous vehicles, biotechnology, nanotechnology, quantum computing, and 3D printing create vast new opportunities to address Earth system challenges, amplified as technologies become increasingly connected (World Economic Forum, 2018). Changing expectations come with this new era: a new generation that wants and expects more accessible, mobile, portable, flexible, and customizable products, services, and experiences. As this new generation becomes incorporated into the ranks of scientists, resource and emergency managers, and policy and decision makers, these same expectations will define how we approach Earth system challenges. Keeping up with the demands of delivering scientific data, products, and services in satisfying ways and recruiting and retaining new science talent will depend on an aggressive adoption of new technologies.

Several of the new technology opportunities stand out in the near term. AI and ML will play an increasingly key role in analyzing and synthesizing our observational and model output data. We have opportunities to train machines to search for patterns in our data, such as early signals of drought, that we might otherwise miss, or to fill missing links in our process understanding. Using AI/ML applications and software, in partnership with the virtually unlimited resources cloud computing provides, enables the USGS tremendous opportunity to advance the technology behind the science.

Blockchain concepts can help us design more effective monitoring networks and surveillance systems, helping to increase early warning lead time and operate these networks more efficiently. As more and more devices, including sensors, become connected to the internet, the IoT can help us understand dynamics, interactions, and movement. The IoT framework will be a regular part of the USGS science culture moving forward. Having devices that collect and send data to cloud-ingest points where tools and services exist should become a normal mode of doing science as the USGS collects, processes, analyzes, and reports our data in the future.

Internet of Things (IOT): The Internet of things (IoT) describes the complex network of physical objects and cyber objects—systems that involve computation, sensing, communication, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet (Boeckl and others, 2019).

Artificial intelligence (AI) is intelligence demonstrated by machines, unlike the natural intelligence displayed by humans and animals. Any device that perceives its environment and takes actions that maximize its chance of successfully achieving its goals. Colloquially, the term "artificial intelligence" is often used to describe machines (or computers) that mimic "cognitive" functions that humans associate with the human mind, such as "learning" and "problem solving" (Poole and others, 1998).

Machine learning (ML) is the study of computer algorithms that improve automatically through experience. It is seen as a subset of artificial intelligence. Machine learning algorithms build a model based on sample data, known as "training data," in order to make predictions or decisions without being explicitly programmed to do so. Machine learning algorithms are used in a wide variety of applications, such as email filtering and computer vision, where it is difficult or unfeasible to develop conventional algorithms to perform the needed tasks (Mitchell, 1997).

Blockchain: Blockchain is a decentralized, distributed ledger technology that records the provenance of a digital asset in an efficient manner with a high level of fault tolerance (Yaga and others, 2018).

Software-defined networking: Software-defined networking (SDN) technology is an approach to network management that enables dynamic, programmatically efficient network configuration in order to improve network performance and monitoring, making it more like cloud computing than traditional network management (Benzekki and others, 2016).

Zero Trust Architectures: Zero trust (ZT) is the term for an evolving set of cybersecurity paradigms that move defenses from static, network-based perimeters to focus on users, assets, and resources. A zero trust architecture (ZTA) uses zero trust principles to plan industrial and enterprise infrastructure and workflows (Rose and others, 2020).

Gig-Ethernet Circuits: Gigabit Ethernet is the term applied to transmitting Ethernet frames at a rate of a gigabit per second (IEEE, 2018).

Quantum computing, still in its early stages, will open new doors for nonlinear process modeling and modeling probabilities and uncertainties without the need for large ensembles. Already used in commercial sensor development, 3D printing creates numerous possibilities for the USGS to innovate and deploy new sensor technologies cheaply and quickly.

An aggressive pursuit of more familiar computational technologies, including HPC and cloud- and high-throughput computing, is essential for the USGS to address the Earth system challenge. ESMs and AI/ML have high but differing computational needs; each has different requirements for computational intensity and access to memory and storage. Computers optimized for one need are generally suboptimal for the other. Both applications will need much greater computational power than is available today, and we will need to use it more efficiently. The USGS has many opportunities, both with its own internal systems and through collaboration with partners, to explore and optimize its computational solutions in the coming decade. Implementation of a cloud computing and long-term HPC strategy in the USGS is a fundamental building block from which our journey begins.

USGS hydrologist flies a small drone equipped with a thermal infrared camera during a groundwater/surface-water exchange study. Photograph by USGS.

Achieving Our Vision

Implementation of the USGS 21st-Century Science Strategy involves five interrelated components:

1. A focus to develop a Bureau-wide, integrative and predictive science capability called Earth Monitoring, Analyses, and Prediction (EarthMAP);
2. A scientific focus to build upon our mission-specific capabilities and drive greater interdisciplinary integration;
3. A technology focus to provide the 21st-century IT and necessary technical innovations;
4. A partnership focus to develop relationships between the USGS and the broader ESS community and to strengthen linkages among Federal, Tribal, State, private sector, academia, and nonprofit organizations; and
5. An organizational focus to optimize interactions across the USGS, develop our workforce, and improve our facilities.

Detailed strategic implementation plans will be developed for each of these components.

View of Glacier National Park, Montana, from the mouth of Reynolds Glacier. Photograph by Joe Giersch, USGS.

1. EarthMAP

To fulfill the vision of a Bureau-wide, integrated predictive science capability, the USGS initiated a multiyear effort to design and build the Earth Monitoring, Analyses, and Prediction (EarthMAP) capability. EarthMAP was a concept originally articulated in the USGS Grand Challenges Integrated Science Workshop, which brought together leading scientists from across the USGS (Jenni and others, 2017). When fully implemented, EarthMAP will link the USGS's capabilities in Earth system characterization science and rich datasets with advanced integrated predictive models that are enhanced through the use of AI/ML and HPC. EarthMAP will allow the USGS to deliver actionable intelligence in the form of integrated observations, scenario planning, and predictions of the future state of the Earth system—at the scales and timelines needed to inform decisions. At all scales, these predictions will account for complex system interactions and will be used to anticipate the likelihood and consequences of evolving threats and hazards, to help guide resilient adaptation and mitigation efforts, and, in ways unimaginable today, to further our Nation's prosperity, ensure our citizens' safety, and support the long-term sustainability of the Earth.

Developing EarthMAP will be challenging. Success will not be easy, nor is it guaranteed. Fiscal constraints and competition for the highly qualified people necessary for development will continue. The USGS will take a methodical and structured approach to implement EarthMAP, requiring new approaches to planning our science portfolios and strategic investments. By 2030, the USGS aims to deliver well-integrated observations and predictions of the future state of natural systems—water, ecosystems, energy, minerals, and hazards—at regional and national scales, working primarily with Federal, State, Tribal, and academic partners to develop and operate the capability.

By using our strategic planning framework (described later in this document), we will carefully plan our science and focus on the knowledge gaps that limit progress towards the EarthMAP vision and identify initial goals for integrated and predictive science that is supported by investments in observations, models, technology, and partnerships. This planning effort will also identify the knowledge base across the entire scientific sector that can be leveraged to achieve this vision.

EarthMAP's integrated predictive capability will cross scientific boundaries and disciplines. It will require investments in data collection and integration and new technology to include HPC, cloud computing, advanced modeling, AI/ML, and visualization and decision-support tools. EarthMAP will deliver powerful new products and services that detect and assess vulnerabilities and anticipate the likelihood and consequences of evolving threats and hazards, and it will provide decision-support tools that help guide resilient adaptation and mitigation efforts (projections and predictions, early warning) at the scale of decisions.

Implementing EarthMAP will require a systems-of-systems engineering approach to analyze the complex suite of processes and systems that compose the Earth system. The processes and systems that will compose EarthMAP are quite different from each other and operate independently, but also display emergent properties (more complex behaviors) and patterns when they interact (fig. 2). Emergent patterns likely evolve over time and must be recognized, analyzed, and modeled to be fully understood.

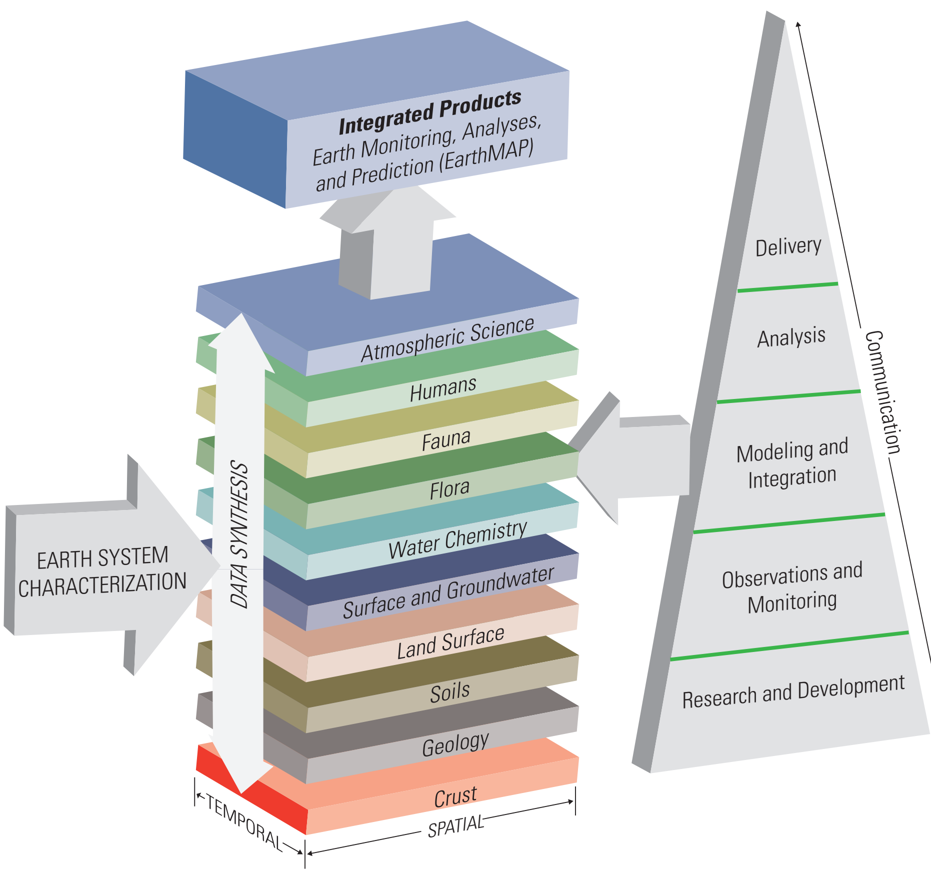


Figure 2. Conceptualization of EarthMAP as a system of systems (modified from Jenni and others, 2017).

2. Scientific Focus

The USGS's vision takes advantage of USGS strengths and its unique position as a science organization with expertise spanning the full range of natural science disciplines, its nationwide presence, its collaboration with stakeholders, and its national and international scope and responsibilities. Over the next decade, we will take advantage of the USGS's rich Earth and biological datasets, advances in sensor technologies, enhanced integrated modeling, ML, and HPC, including cloud computing, to observe, understand, and predict change across spatial and temporal scales, in real time and in a predictive manner.

Under this vision, USGS mission areas will work together to provide significant advances in our ability to

- Monitor and assess availability and quality of the Nation's freshwater supply by implementing new and advanced observing systems, developing advanced predictive water resource models, and developing routine operational national predictions of water availability;
- Provide natural hazard risk-characterization tools and deliver real-time situational awareness that can be used to enable communities and landscapes to become more resilient;
- Provide ecological modeling and forecasting to provide actionable intelligence to managers at the scale of decisions;
- Provide state-of-the-art species management scenarios, assessments, and distribution maps for Department of the Interior trust species;
- Detect and control invasive species and wildlife diseases before they become established and potentially affect human health and well-being;
- Characterize the Earth and its processes more accurately and provide 3D data, maps, and models that enhance scientific insight and enable new applications in the management of the Nation's public lands and resources;
- Assess energy and mineral resources across the Nation and around the globe through integrated, interdisciplinary assessment of the full life cycle of those resources; and
- Expand the Nation's understanding of the location, availability, and supply-chain risks for energy and mineral resources necessary to support national security and the development of infrastructure and new technologies.

USGS microbiologist preparing a water sample. Photograph by Ian M. Hyslop, USGS.

3. Technical Focus

The USGS will achieve technical excellence that will deliver 21st-century IMT to its scientists and the many users who rely on USGS knowledge and products. These components include cloud computing, sensor and network expansion, information and data management, advanced hyperconverged infrastructure, AI/ML, visualization tools, and enterprise-wide cybersecurity.

The USGS will:

- Leverage cloud solutions in conjunction with cutting-edge cloud tools and services to provide on-demand, scalable computing infrastructure in support of complex scientific modeling in near real time with access to very large datasets in order to realize the new paradigm for scientific computing and analysis;
- Expand the sensor network by increasing the number and sophistication of sensors to streamline the collection of data for research and analysis;
- Increase the bandwidth and efficiency of the sensor network to move the collected data to the cloud and accelerate the performance of the scientific analysis;
- Modernize the data network through software-defined networks and Zero Trust Architectures to support 21st-century scientific needs;
- Utilize improved information and data management to support the USGS's predictive science capability;
- Expand data sources and collection methods with a focus on accessible data across the USGS;
- Incorporate new methods and more diverse data into predictive science;
- Enhance integrated modeling by enabling new data management technologies;
- Utilize hyperconverged infrastructure to fully achieve the EarthMAP vision;
- Develop a modern, highly available infrastructure;
- Leverage the newest in server and virtualization advancements;
- Create AI/ML and visualization tools for effective data analysis at the source of collection for identification of patterns and enabling actionable intelligence; and
- Utilize visualization tools to communicate our information in order to enhance understanding of the decision-support capabilities produced by EarthMAP.

4. Partnership Focus

Effective partnering is critical to our success in the 21st century. Collaboration with partners will bring to light science questions and needs that we can work together to address. We will leverage existing relationships and develop new relationships among Federal agencies, other governmental agencies, State geological surveys, Tribal governments, the private sector, academia, and nongovernmental organizations.

By partnering and collaborating with stakeholders and other science entities whose work supports, complements, or extends our own, the USGS can better align our efforts and focus our investments on what the USGS can best contribute. This will include the following:

- Improve coordination with the broader Earth observations community—multiple agencies and organizations that actively collect relevant Earth observations in situ and remotely—to expand accessibility of all the data needed to address the Earth system challenge;
- Enhance partnerships with Federal agencies, academia, and others in the Earth system modeling community to strengthen our science and broaden our leadership opportunities;
- Foster technological collaborations across Federal agencies and academia to better leverage HPC and high-throughput computing assets, establish common-purpose community development testbeds, co-develop new sensor innovations, and accelerate implementation of advanced technologies; and
- Engage with stakeholders and decision makers who rely on our science to carry out actions to mitigate riverine and coastal flooding, perform ecosystem restoration, manage inland freshwater fisheries, manage critical mineral and energy resources, track and mitigate invasive species and wildlife disease, mitigate coastal erosion, and make a host of other important decisions.

5. Organizational Focus

The realization of the USGS's vision and mission depends on its people. As history has demonstrated, it is our people—highly skilled, innovative, well trained, and led by individuals with a clear commitment to our mission and values—who make the USGS successful. First and foremost, we will ensure a safe, secure, and inclusive environment for our workforce, where employee contributions are recognized in support of our collective efforts. The USGS will ensure a welcoming and inclusive environment that prevents all forms of discrimination and harassment. The USGS is committed to a workplace—whether physical or virtual—in which all people, regardless of their race, color, gender, ethnicity, national origin, age, sexual orientation, or physical or mental disability, are treated with dignity and respect. Education and outreach strategies will address how the USGS will increasingly focus on recruiting women and minorities in areas underrepresented in STEM as well as within the science support workforce.

We will identify and pursue opportunities for employees to develop new skill sets; develop a resilient workforce that can adapt to changes in mission requirements and advancements in technology; create an integrated talent management model that addresses the entire span of employees' careers; and develop workforce analytics that measure success.

Pursuing the Earth system challenge has implications for our workforce, and we must plan for how we take on this vision through a team-of-teams approach encompassing continuous improvement, problem solving across organizational boundaries, and working collaboratively towards common goals. We must ensure our current workforce is prepared to take on this vision, while at the same time, recruiting and retaining new team members with diverse and complementary technical skills. In addition, we must expand the pathway into the USGS for early career scientists and other professionals from diverse and interdisciplinary backgrounds.

The success of our workforce depends on the availability of unique facilities, tools, capabilities, and services to successfully conduct our mission. To plan, operate, and sustain this infrastructure and our essential services, several critical operational capabilities are required, including management of finance, real property, and other support functions. These science support functions are integral to the success of the mission and are essential to moving this vision forward.

As we implement this vision, every USGS employee will play a role. We will carefully consider the USGS footprint to ensure we are appropriately placed on the landscape to efficiently and successfully execute the mission, ensure implementation of our concept of operations which clearly outlines the roles and responsibilities of those in the Bureau, and implement longer planning horizons, with accountability and traceability of USGS activities through requirements management. As stewards of the taxpayers' dollars, these actions will continue to ensure we are effectively planning and managing for success in the vital USGS mission.

USGS research geologists discuss the project area around Lake Clark National Park and Preserve, Alaska. Photograph by Erin Todd, USGS.

Strategic Planning Framework

The USGS strategic planning framework includes decadal planning horizons, cross-portfolio integration, and innovative partnerships among the whole of the science community, including the private sector, academia, nonprofit organizations, and government agencies. Strategic investments are needed for the USGS to deliver on its commitments to our stakeholders. The USGS will prepare and implement an integrated 5-year Science Plan to support this 21st-Century Science Strategy, detailing how we will achieve our current mission while also making steps towards implementing new priorities. The strategic planning framework will guide our decision-making processes as we execute the USGS mission and vision over the coming decade.

Bison at Rocky Mountain Arsenal National Wildlife Refuge, Colorado. Photograph by Stephanie Raine, U.S. Fish and Wildlife Service.

Core Values

USGS core values guide individual and organizational behavior. They also guide USGS leaders in making decisions. Constant attention to these core values leads to mission success:

- Service to the Nation—The USGS maintains a strong service culture and believes our science must lead to actions that make people's lives better. We will be rigorous in how we prioritize the work we do and focus on the biggest challenges that face humanity today.
- Partnerships—Effective partnerships are critical to ensuring success in the 21st century. The USGS will leverage partnerships across multiple sectors—Federal, State, local, and Tribal governments, the private sector, and academia.
- Diverse and Highly Skilled Workforce—Innovation thrives on the inclusion of diverse talents from all levels and segments of the organization in achieving the vision and mission of the USGS. The USGS philosophy is that all team members bring unique expertise and knowledge to our scientific endeavors. A work environment that is open and inclusive to differing ideas and insights increases the likelihood of mission success. Engaging young people in USGS science helps to ensure the highly skilled USGS workforce of the future.
- Scientific Integrity—The reputation of the USGS is central to the Bureau's mission and fundamentally protects the credibility of its science. Throughout its 142-year history, the USGS has worked to build a reputation for objective, unbiased science in service to the Nation. Every USGS employee, from early-career scientists, to administrators, to senior leadership, has a role to play in upholding and protecting our scientific integrity, maintaining an ethical culture beyond reproach, and ensuring that Fundamental Science Practices are followed. The American people have placed their trust in each of us to conduct ourselves with integrity, and as such, we will all be held accountable to the highest ethical standards.
- Safety—The USGS is committed to protecting the health and safety of everyone involved in USGS science activities.
- Team-of-Teams Approach—The USGS is a team of teams, and we will address society's needs with an integrated approach that brings together the combined strength of our science disciplines, mission areas, and regions.

Two USGS employees using an acoustic Doppler current profiler to make an under-ice discharge measurement near a USGS streamgage, Copper River at Million Dollar Bridge near Cordova, Alaska, February 2020. Photograph by USGS.

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Unoccupied aircraft system is inspected just before takeoff to collect water from the Halema'uma'u crater lake, Hawaii Volcanoes National Park, January 2020. Photograph by Joe Adams, USGS.

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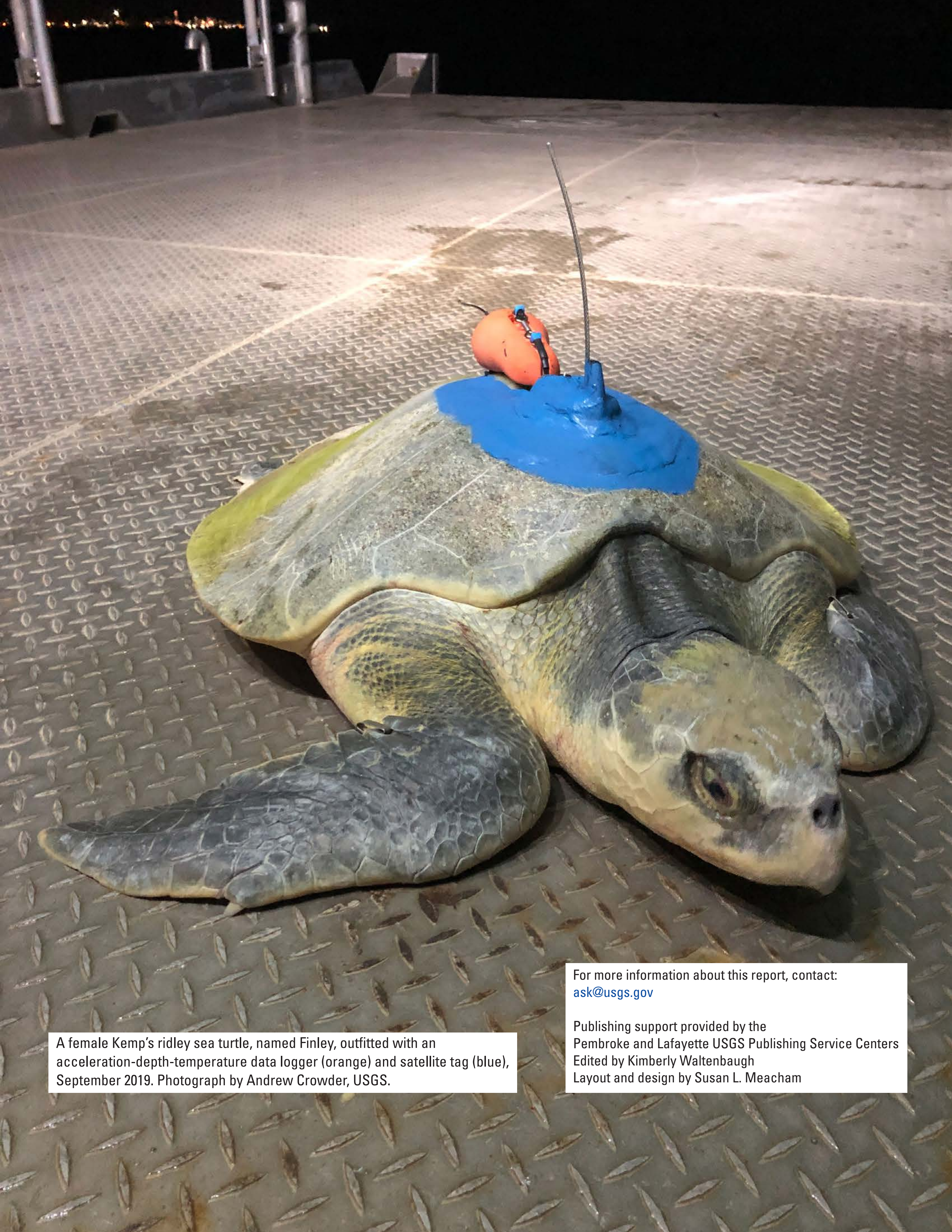
USGS scientist conducts a photographic survey of Porter Patch reef off Key Largo, Florida, 2019.
Photograph by Dominique Gallery, USGS.



A female Kemp’s ridley sea turtle, named Finley, outfitted with an acceleration-depth-temperature data logger (orange) and satellite tag (blue), September 2019. Photograph by Andrew Crowder, USGS.

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