Understanding Dynamics and Resilience in Complex Interdependent Systems

Prospects for a Multi-Model Framework and Community of Practice

Report of a workshop held under the auspices of the U.S. Global Change Research Program Interagency Group on Integrative Modeling with support from the U.S. Department of Energy

U.S. Global Change Research Program

Disclaimer

This document was prepared by an ad hoc scientific group as a general record of discussions during the workshop and associated meetings. The document captures the main points and highlights of these discussions and includes brief summaries of presentations and work group sessions. It is not a complete record of all details discussed. Statements represent the views of the authors and not of any U.S. federal agency.

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Richard H. Moss[1], Karen Fisher-Vanden[2], Alison Delgado[1], Scott Backhaus[3], Christopher L. Barrett[4], Budhendra Bhaduri[5], Ian P. Kraucunas[1], Patrick M. Reed[6], Jennie S. Rice[7], Ian Sue Wing[8], Claudia Tebaldi[9]

[1] Pacific Northwest National Laboratory
[2] Pennsylvania State University
[3] Los Alamos National Laboratory
[4] Virginia Tech
[5] Oak Ridge National Laboratory
[6] Cornell University
[7] Smarter Decisions, LLC
[8] Boston University
[9] National Center for Atmospheric Research

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Interagency Coordinating Group

Robert Vallario, U.S. Department of Energy (ICG Chair)
Gerald Geernaert, U.S. Department of Energy (USGCRP Vice-Chair)
Gregory Anderson, National Science Foundation
Jeffrey Arnold, U.S. Army Corps of Engineers
John Balbus, National Institutes of Health
Hoyt Battey, U.S. Department of Energy
Diana Bauer, U.S. Department of Energy
Jessie Carman, National Oceanic and Atmospheric Administration
Paul Cohen, Defense Advanced Research Projects Agency
Charles Covel, U.S. Department of Homeland Security
Benjamin DeAngelo, U.S. Global Change Research Program
Anne Grambsch, U.S. Environmental Protection Agency
Fiona Horsfall, National Oceanic and Atmospheric Administration
Margaret Lange, National Geospatial-Intelligence Agency
Michael Lenihan, National Geospatial-Intelligence Agency
Jia Li, U.S. Environmental Protection Agency
James McFarland, U.S. Environmental Protection Agency
Robert O'Connor, National Science Foundation
Marilee Orr, U.S. Department of Homeland Security
Alexander Ruane, National Aeronautics and Space Administration
Ronald Sands, U.S. Department of Agriculture
ICG Coordinator: Alison Delgado, U.S. Global Change Research Program/PNNL

Scientific Steering Group

Scott Backhaus, Los Alamos National Laboratory
Christopher Barrett, Virginia Tech
Budhendra Bhaduri, Oak Ridge National Laboratory
Karen Fisher-Vanden, Pennsylvania State University (Co-Chair)
Ian Kraucunas, Pacific Northwest National Laboratory
Richard Moss, Joint Global Change Research Institute, PNNL (Co-Chair)
Patrick Reed, Cornell University
Jennie Rice, Smarter Decisions, LLC
Ian Sue Wing, Boston University
Claudia Tebaldi, National Center for Atmospheric Research

About the Interagency Group on Integrative Modeling

The Interagency Group on Integrative Modeling (IGIM) of the United States Global Change Research Program (USGCRP) coordinates global change-related modeling activities across the Federal Government and provides guidance to USGCRP on modeling priorities. The 10 Federal agencies that participate in the IGIM engage on a range of relevant topics, including physical models of the Earth system, socioeconomic models of human systems and their interactions with the Earth system, and impacts models.

Acronyms and Abbreviations

CESM	Community Earth System Model
CSDMS	Community Surface Dynamics Modeling System
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
ES	Earth systems
ESM	Earth systems models
GCM	Global Climate Model
GHG	Greenhouse gas
HSPF	Hydrological Simulation Program-Fortran
IA	Integrated assessment
IAM	Integrated Assessment Models
IAV	Impacts, adaptation and vulnerability
ICG	Interagency Coordinating Group
IGIM	Interagency Group on Integrative Modeling
LIDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NISAC	National Infrastructure Simulation and Analysis Center
NOAA	National Oceanic and Atmospheric Administration
PRIMA	Platform for Regional Integrated Modeling and Analysis
RIAM	Regional Integrated Assessment Modeling
SSG	Scientific Steering Group
TMDL	Total Maximum Daily Load
USGCRP	United States Global Change Research Program
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture

Executive Summary

This report describes the results of a workshop that addressed the challenge of developing coupled modeling and analysis of interdependent energy, land, and water systems. It has been prepared by a group of scientists who participated in the workshop process. The views expressed are those of the authors. The report includes short summaries of workshop presentations and breakout group discussions. It considers the opportunity to develop an interdisciplinary framework for data, modeling, and analysis of complex human-natural systems.

Infrastructure, natural, and socioeconomic systems are tightly coupled through flows of materials, energy, water, and other resources, as well as through governance structures and institutions. These systems are rapidly co-evolving and transforming through interdependent yet independent decisions driven by socioeconomic and environmental change. The norm in current research and analysis is to consider how *individual* sectors are influenced by these multiple forces. Yet there is increasing evidence about the importance of including cross-sectoral and cross-scale interactions in modeling to understand the resilience of even individual infrastructure systems, let alone more complex interdependent networks of systems. The workshop explored related research questions, their societal importance, available capabilities, and options for accelerating this area of complex systems science.

The workshop was convened by a set of Federal agencies under the auspices of the U.S. Global Change Research Program that have an interest in developing and applying data sets, computational resources, and models to improve knowledge of complex systems. The participating agencies, state and local governments, private-sector firms, regional planning authorities, and others have a shared interest in understanding how interdependencies and feedbacks could lead to cascading failures and shocks resulting from interacting changes in climate, settlement patterns, and other stressors, and from emerging properties of the systems themselves.

The workshop focused on examples in two broad areas: understanding processes and dynamics of co-evolving concentrated, connected infrastructure, and understanding implications of drought and increased hydrological variability at scales from local to international. The workshop identified scientific questions related to the complex systems themselves, as well as in three related areas of research: Earth systems (ES) science, the study of potential climate change impacts, adaptation and vulnerability (IAV), and integrated assessment (IA) of coupled human-environment systems. The purpose of focusing on the cases and these areas of research was to explore an overall conceptual framework that bounds the systems, identifies constituent subsystems, and defines the various levels of detail, complexity, and spatiotemporal resolution needed to address specific questions. No effort was made to reach a consensus about this framework, and a variety of disparate viewpoints were expressed.

Considering the scientific questions and the examples of co-evolving interdependent systems discussed throughout the workshop, participants identified a possible overarching objective of the framework to "develop an interconnected system of models, data, analysis, and decision support capabilities that help build resilience in interdependent systems". The agency program managers, scientific steering group members, and workshop participants stressed the potential societal relevance of the modeling framework. Considering the need to guide scientific progress so that it results in usable knowledge, many participants suggested a challenge that the research and user communities should work together to develop the framework.

In addition to a nearly universal sense that the term "framework" does not imply a single model with fixed components and configurations, a number of key characteristics or components of a framework were identified. The framework needs to incorporate a modular, interoperable, and agile approach to link specialized data sets and models of relevant systems spanning climate, critical infrastructure systems, natural resources, agroforestry, and socioeconomic systems. It needs to be able accommodate interactions of these many processes and subsystems across geographies and time scales. The conceptual structure needs to define system boundaries and subsystems, and to clarify the relationships and information flows across a hierarchy of models and spatial/temporal scales. Data and models relevant to the wide range of different processes and systems considered here can be expected to differ in important respects, including time and spatial scales, variable names and units, programming languages, and other characteristics. Thus the framework will need to provide a variety of tools for reconciling differences that would otherwise prevent exchange of information across component models, data sets, and analytical methods.

The workshop identified numerous extant models, data sets, computational resources, and analytic tools that can serve as an initial foundation. New capabilities are needed in several areas including fine-scale population/demographic distribution models; individual networks and systems at both high resolution and in aggregate statistics on network performance; representations of human behavior beyond economics; modeling of extreme events at relevant spatial and temporal scales; ability to model socioeconomic shocks; information and methods to represent how different governance and institutional mechanisms affect function and resilience; development of emulators of complex models; methods for measuring and communicating uncertainty and precision; and other specific needs. The workshop pointed to the need to address issues of model validation and uncertainty characterization that remain challenges for many of the individual capabilities, let alone to coupled models of complex systems in which uncertainties propagate across capabilities.

The workshop addressed needs for enabling capabilities to support collaboration among investigators pursuing their own research within a broader community by facilitating interoperability of models, data, and methods. Examples of these services include naming conventions for variables and processes, data management, geo-visual analytics, data conversion, integration and mining algorithms, software and scalable computer resources, and other tools.

Considering the degree of complexity in interactions across natural resources, infrastructure, socioeconomic, and Earth system processes, the diversity of disciplines and tools involved, and the emphasis on use-inspired science, the workshop identified several options for establishing a "community of practice" to accelerate progress. A key challenge is to focus on integration and to establish incentives to make models, data, and other tools relevant beyond the immediate context in which they were developed and accessible to others. Immediate or near-term options for next steps include: establish expectations among participating scientists regarding transparency and accessibility to their work; develop a use typology; identify system elements common to multiple cases; inventory and evaluate existing capabilities; define needed information flows and coupling strategies; establish enabling capabilities such as naming conventions, data management, and other tools; and conduct coordinated experiments to promote evaluation and uncertainty analysis. One idea that grew out of the workshop was a suggestion to establish a network of *"regional test beds for data modeling and analysis"*. These test beds could be coordinated around priority problems in different regions and would be used to develop and evaluate combinations of data and models needed to address the problems. The test beds would provide practical examples of the utility of the integration of observational data, modeling, analytic, and decision-support tools spanning scales and systems and provide opportunities for establishing the community of practice.

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I. Introduction: understanding the dynamics of co-evolving interdependent infrastructure, environmental, and socioeconomic systems

1.1 Motivation

Understanding the dynamics of co-evolving, interdependent infrastructure, environmental, and socioeconomic systems is an area of scientific opportunity and societal need. Advances in global change research, data analytics, computer science, and other fields are leading to the development of new tools to explore how climate change and other stressors will interact with interdependent critical infrastructure systems, ecosystems, human development patterns, and institutions to affect resilience of communities at scales from local to global. Opportunities exist to improve our understanding of the interdependencies and their consequences – how interactions among the many components of these systems will produce emergent properties that affect vulnerability and resilience, and the ways in which routine planning and investment decisions today could shape those interactions. Realizing these opportunities will require integrating data, modeling, and analysis in a problem-driven framework that facilitates if-then analysis under conditions of deep uncertainty.

This report describes the results of a workshop and allied activities that are exploring opportunities to address the challenge of developing coupled modeling and analysis of interdependent systems, with a focus on energy, land, and water systems. The workshop was convened by a group of Federal agencies under the auspices of the U.S. Global Change Research Program (see Appendix A and E for the workshop program and participants list). As will be described in the report, the agencies have an interest in advancing scientific theory and applying data sets, computational resources, and models to improve knowledge of complex human and natural systems as they undergo rapid transformations driven by environmental and socioeconomic forces. The agencies recognize that different infrastructure, natural, and socioeconomic systems are tightly coupled through flows of materials, energy, water, and other resources, as well as through economics, governance structures, and institutions. They are increasingly confronting the need to better understand the implications of environmental, socioeconomic, and other changes. One prominent example involves increasing use of energy to move water across basins in response to water stress resulting from changing demand, groundwater depletion, changes in land use/runoff, and changes in timing, type, and volume of precipitation, among other factors (Figure I-1).

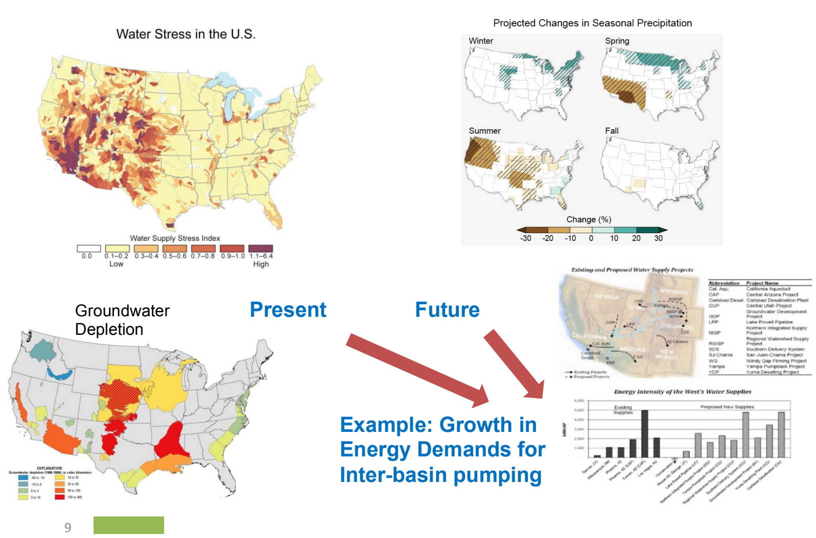


Figure I-1. Growth in energy demands for inter-basin pumping of water resources. Source: Robert Vallario, U.S. DOE.

A widely shared concern is how interdependencies and feedbacks could lead to cascading failures that result from shocks related to interacting changes in weather patterns, settlements, and other stressors, and from emerging properties of the systems themselves. For example, extreme weather can damage utilities such as electric power, water, and communication, resulting in interruptions in other activities such as oil/gas refining and transport, with further implications for provision of healthcare, the economy, and communities. The participating agencies also recognize that state and local governments, private-sector firms, regional planning authorities, and others face similar challenges, and that a set of agile, flexible, interoperable tools for modeling and understanding the interactions of infrastructure, environmental, and socioeconomic systems would advance both scientific and societal objectives.

The motivation for this workshop and related activities is to develop an interconnected framework of data, modeling, and analytic tools to study the behavior of complex interacting Earth, environmental, infrastructure, and socioeconomic systems. This framework can build on increasing integration of Earth systems, sectoral, and integrated assessment modeling that is already underway (see Figure I-2). Because different categories of research questions and/or decision problems are likely to require different combinations of research and modeling capacity, an important characteristic of this framework will be its ability to combine diverse types of modeling and analysis as-needed. A key capability within the framework is the ability to integrate models of varying levels of complexity to support analysis of uncertainty and to explore connected risks and potential strategic responses, e.g., at the energy-water-land (including food) nexus, or for cascading risks of connected infrastructure. A further challenge is to develop these tools and knowledge in a collaborative fashion that engages both the research community and potential users in government and the private sector so that the resulting tools and knowledge will support a more resilient economy, nation, and global community.

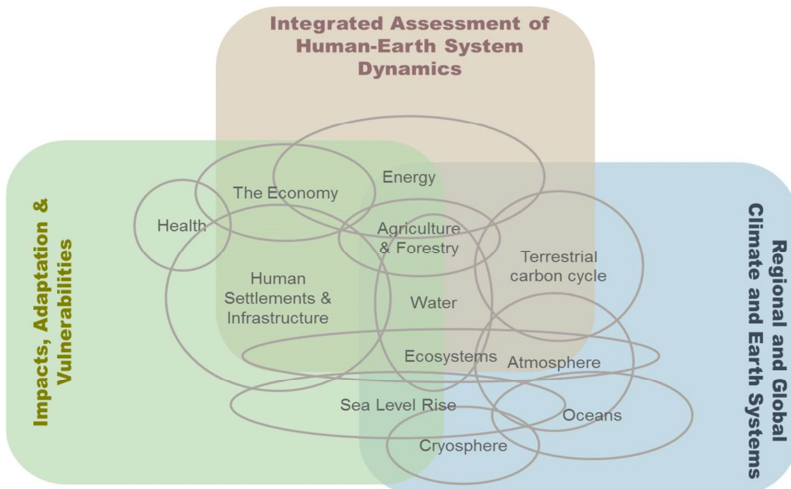


Figure I-2. Models of the Earth systems, infrastructure and natural resource systems, and integrated assessment of human-environment systems are becoming increasingly linked and provide a foundation for development of a new framework for data, modeling, and analysis of complex, co-evolving systems. Source: U.S. DOE, *Science Challenges and Future Directions: Climate Change Integrated Assessment Research*, 2009.

I.2 Scientific context

Exploring opportunities for an interdisciplinary framework to address these issues is part of a broader process underway in both the research community and the Federal agencies to integrate data, modeling, and analysis to address science questions and develop capabilities that can be applied to improve information for decision making.[1] The effort will require drawing upon a large number of disciplines and research areas.

[1] Appendix D contains recent examples of DOE activities that call out the need for such a framework.

Complex Adaptive Systems

Fundamentally, concepts and methods will need to build on the study of complex evolutionary systems including systems theory, nonlinearity and chaos theory, network theory, and the science of complex adaptive systems and self-organization. Underlying scientific issues include understanding how complex systems evolve and operate through self-organizing, adaptive processes, the extent and ways in which different choices about configurations of components and governance structures affect system performance and other properties, and how a variety of shocks—climate-related and socioeconomic—could affect the evolution and function of system elements.

While complex systems theory provides a fundamental underpinning, most of the scientific focus of these endeavors for understanding global change and its socioeconomic and environmental impacts falls in three related areas of research: Earth systems (ES) science; the study of potential climate change impacts, adaptation, and vulnerability (IAV); and integrated assessment (IA) of coupled human-environment systems.

Earth Systems Science

Relevant areas of Earth systems science focus on understanding interactions of natural variability and anthropogenic climate change, and the manifestations of these forces in regional and even local patterns of changes in average and extreme conditions such as heat waves, droughts, intense storms and precipitation, sea-level change, and other events. Earth systems models (ESMs) integrate a range of component models of the climate system, atmospheric chemistry, terrestrial ecosystems and land cover/use, and hydrology. Climate scientists have also developed a variety of methods for downscaling model results to higher resolutions needed for many impacts analyses. Earth and climate observations will also be essential.

Impacts, Adaptation, and Vulnerability Models

Research on the impacts, adaptation, and vulnerability of different systems focuses on the effects of interacting Earth system, socioeconomic, and environmental changes on a wide range of built and natural systems. Research and associated methods are extremely diverse and borrow from modeling and other studies focused on infrastructure (e.g., energy, water resources, flood control, transportation, health, communications), ecosystems (e.g., agriculture, forestry, land cover/use, marine, aquatic), and socioeconomic processes (e.g., migration, economic development, tourism). The scale of analysis of these models can vary widely, from incorporating detailed network physics at local scales to analysis of global shifts in ecosystems, land use, and agricultural productivity. Models typically represent physical flows and variables, which provides strength in understanding the direct interactions and relationships across sectors and activities. These approaches stand in contrast to integrated assessment models (see next section) that incorporate markets and shifts in supply and demand and can be used to represent institutions and governance arrangements.

Integrated Assessment Models

IA integrates ES, IAV, and economic modeling, often in reduced form, to study interactions of systems and evaluate the implications of uncertainty. Like IAV research, integrated assessment research is also diverse. Integrated Assessment Models (IAMs) often represent energy technology systems in great detail, incorporating information on cost and performance characteristics, and they are increasingly incorporating detailed representations of land use and hydrology. IAMs can also be used to represent less tangible aspects of complex systems such as policies and institutions. Simple IAMs capture economic flows and damages in reduced form and are useful for stylized evaluation of the implications of a wide range of uncertainties.

As will be discussed below, a key issue is the level of complexity in modeling required to explore these scientific questions. A characteristic of the scientific issues addressed is that they simultaneously require some systems or processes to be represented in depth, and others to be represented in aggregate forms in order to set boundary conditions and account for interactions across multiple levels or systems. Though some systems modeling frameworks often provide reduced form representations of complex systems (e.g., system dynamics, agent-based), these frameworks may not necessarily be suitable on their own to address the questions raised here because of the importance of processes with high resolution, high frequency, and/or feedbacks to understanding how different components of the complex systems under consideration will respond to interacting stresses. The appropriate level of complexity will minimize data requirements, computational intensity, and sources of uncertainty, while maintaining the fidelity and granularity needed to answer the research question. The selection of models and decisions about how they are integrated must manage these tradeoffs in a way that is transparent and repeatable.

I.3 Societal relevance

As described briefly above, a number of Federal agencies already play a critical role in developing scientific capabilities for ES, IA, and IAV modeling that are being used by diverse stakeholders and decision-makers. Development of the modeling framework discussed at this workshop will build added scientific insight and capacity needed to create decision-support tools that will help Federal agencies, state/local governments, regional authorities, and private-sector entities better understand how their decisions and options could interact with environmental and socioeconomic systems evolving under conditions of deep uncertainty.

Agencies participating in this workshop identified many different modeling needs related to investment and adaptive management in a wide range of sectors and activities including energy, water, agriculture, critical infrastructure, environmental and ecosystems management/conservation management, urban and regional planning, economic planning, and evaluation of alternative development pathways. Example modeling needs included:

- Modeling the implications of change in socioeconomic systems, technologies, Earth systems, and other factors for infrastructure systems on scales from regional to local to understand characteristics and requirements of a variety of infrastructure systems;
- Managing alternative development pathways for infrastructure, socioeconomic, and natural resource systems in interdependent energy-water-land systems;
- Modeling to support place-based analysis of the likelihood of Earth system events that could produce shocks that would interrupt infrastructure and pose risks to communities;
- Using coupled, spatially-explicit IAV-IA models to gain foresight from observations, representation of social network data, and other information sources;
- Downscaling of socioeconomic, land use/cover, hydrological, climate, and other scenarios for use in a wide range of planning and investment decisions;
- Modeling a rapidly diversifying energy system as it accommodates changes in demand and prepares for a variety of stresses, including the implications of increasing demand for energy to process and distribute water resources;

- Modeling infrastructure and institutional requirements to simultaneously provide water for sustainable economic growth during periods of drought and to manage floods affected by increasing intensity of the hydrologic cycle;
- Improving information on health and environmental quality effects of interacting changes in land use, climate, socioeconomic conditions, and other factors;
- Analyzing interacting impacts of changes in weather patterns on agricultural productivity, prices, and food security across regions and different cropping and livestock systems, including implications for international trade;
- Analyzing carbon sequestration resulting from various land-based agriculture and energy system mitigation strategies;
- Exploring implications of different scenarios and management options to manage risk, including infrastructural risks.

These examples all involve interdependence of complex system components across time and spatial scales, as well as interactions of these components with uncertain (and in some cases randomly occurring) events such as extreme weather patterns or other natural disasters. Decisions taken in the near term will have long-term implications for the stability and resilience not just of a single resource or infrastructure system, but for a complex of coupled, interdependent systems, and ultimately for human health, safety, and well-being.

I.4 This report

This report has been prepared by a group of scientists who participated in the workshop process. The views expressed are those of the authors. In Section II, we briefly describe the organization of the workshop. In Section III, we interpret the outputs of the workshop presentations and discussions in the context of emerging national needs and ongoing research. We consider what the examples of co-evolving infrastructure, environmental, and socioeconomic systems discussed in the breakout groups indicate about information needs (Section III), objectives and conceptual frameworks (Section IV) and requirements for modeling, data, analytic, and enabling capabilities (Section V). Along the way, the report discusses scientific questions and challenges for this research and, given the ways the different systems interact across spatiotemporal scales and sectors, the implications for the types of model coupling that will be required. The report concludes with ideas for building a community of practice that could help integrate different areas of science, ongoing research activities of Federal agencies, and development of tools to address integration, evaluation, uncertainty characterization, and other challenges (Section VI). The final subsection of the report explores opportunities and potential benefits of developing a set of regional test beds to accelerate development of this area of research.

II. Focus, goals, and organization of the workshop

Against this backdrop, an Interagency Coordinating Group (ICG) of Federal research program managers convened a workshop in College Park, MD on May 24-26, 2016 to develop concepts for a modeling framework or architecture that couples IAV models, IA models, and complimentary ES, climate, hydrology, land use, demography, and other models. The ***IA-IAV-ESM Workshop: Toward Multi-Model Frameworks Addressing Multi-Sector Dynamics, Risks, and Resiliency*** was held under the auspices of the United States Global Change Research Program's (USGCRP) Interagency Group on Integrated Modeling (IGIM), with the sponsorship of the U.S. Department of Energy (DOE). It was organized by the ICG with support from a Scientific Steering Group (SSG) (see front matter for membership lists of these groups). The workshop brought together over 50 experts from the Federal government, academia, national laboratories, and private organizations. Participating agencies and scientists shared a common interest in the scientific challenges associated with modeling the interactions of human and environmental systems to support risk management of evolving human-environmental systems. The workshop agenda and background materials are included in appendices at the end of the report.

The workshop was structured to address the following challenges:

- *Systematize needs and uses*: Workshop participants explored uses, scale and information dependencies associated with these uses, and specific information needs for categories of problems. Discussions at the workshop were intended to help development of a "use typology" that would help identify needs to guide research and development of the framework.
- *Inventory and evaluate the state of science*: Participants addressed the need to inventory extant and emerging models and frameworks for representing and integrating key processes and interactions. This includes evaluating sector-specific IAV models (ranging from those focused on resource productivity to market interactions), IAMs, a range of approaches for characterizing changes in climate and related physical systems (e.g., hydrology, land cover), and methods for modeling socioeconomic systems and behavior. In addition, participants explored data requirements, coupling strategies, mechanisms to capture impacts and adaptation information that is not amenable to modeling, approaches for evaluating risk, and model evaluation.
- *Explore conceptual frameworks*: Participants discussed options for developing a conceptual framework for research and modeling that defines data and coupling needs by identifying interactions across scales, sectors, and temporal processes essential for addressing the problems and information needs. Also, participants explored the near-term mechanisms and activities for implementation of the framework concept in ongoing and planned model development activities across the agencies and interested research community.
- *Identify research needs/opportunities to improve data, modeling, and analysis of key processes and uncertainties*: The workshop explored needed advances in fundamental research on Earth systems, environmental, and societal processes; specialized sector-specific models; and models able to represent interactions and tradeoffs across sectors, systems, and time/spatial scales that can contribute to advancing the state of science. This included addressing research gaps and priorities for different intended applications and user communities.

The flow of information on needs, capabilities, and options for developing a modeling framework are illustrated in Figure II-1.

The workshop was conceived from a strong shared agency interest in the dynamics of the human-environmental systems using coupled modeling of interlinked energy, land, urban infrastructure, water, and health systems that are increasingly being shaped by extreme events. The need to respond in a more coordinated way to the opportunities and challenges of developing IAV-IA modeling frameworks was first identified at a side meeting on July 30, 2015 at the annual meeting on Climate Change Impacts and Integrated Assessment in Snowmass, CO.

Early discussions of the USGCRP ICG emphasized the need for development of a new class of modeling and related decision-support capabilities that would link current IAV models and IAMs, including potential linkages with other model types, such as regional and global climate models, demographic models, and hydrology models. Past efforts to couple these models have been mostly ad hoc, often miss important sectoral and spatial linkages and feedbacks, and do not take advantage of developments in computing power and analytic methods. The ICG also expressed interest in developing improved visualization and other decision-support methods.

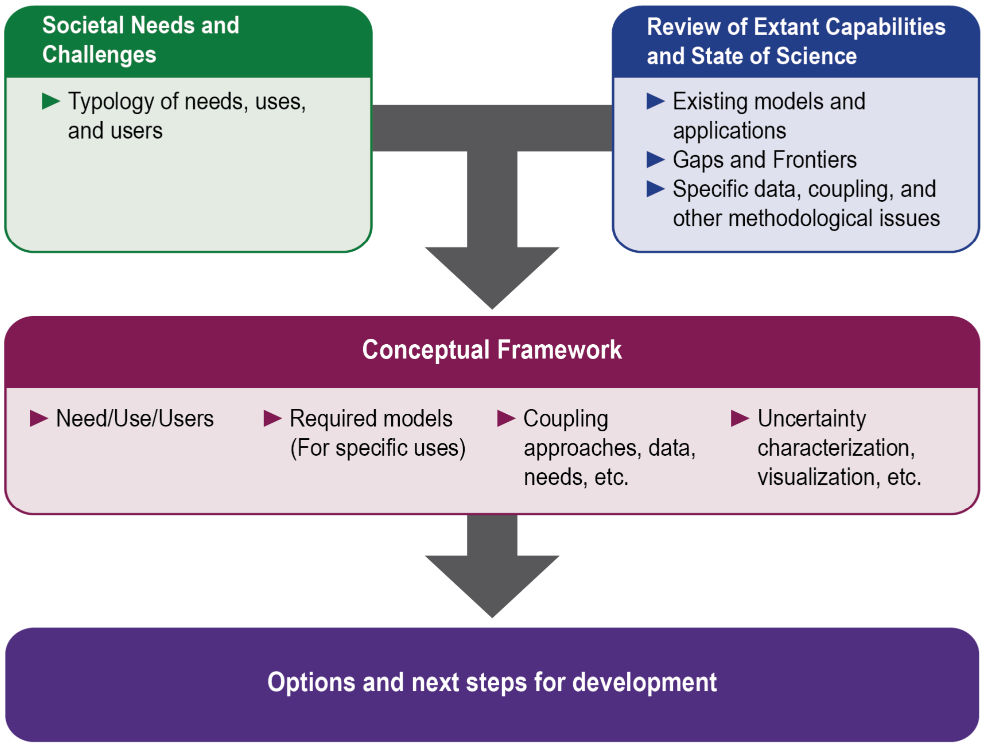


Figure II-1. Needs, capabilities, and options for developing a modeling framework. Source: U.S. DOE, *The Water-Energy Nexus: Challenges and Opportunities*, 2014

Early discussions of the ICG focused on identifying a small number of likely integrative themes or use applications for the workshop. Some of the primary drivers/factors of interest included infrastructure, energy, land, water, global change, migration, health, and socioeconomics. The ICG felt that behavioral (human and institutional response) factors are equally important. In addition, the group identified uncertainty as a cross-cutting theme, rather than a single factor or driver. The consensus was to focus the workshop on the following two integrative themes that effectively spanned areas of interest as well as spatial and temporal scales:

1. Concentrated and connected infrastructure;
2. Drought and increasing hydrologic variability.

The ICG and SSG worked together to organize the agenda for the meeting, which was structured as follows:

- Opening presentations described needs, ongoing research activities, and preliminary ideas about the elements of useful frameworks for data, modeling, and analysis.
- Several presentations described advanced modeling approaches including integrative frameworks, modeling of infrastructure networks, and micro-scale, agent-based modeling of micro-scale individual behavior and institutional response.

- The remaining two and a half days focused on parallel breakout groups and synthesis discussion in plenary sessions. The breakout groups were assigned to discuss information needs of specific users, to select specific model outputs/metrics that would be useful in addressing their needs for information, and then to discuss capabilities for data, modeling, and analysis that were required.
  - The first set of breakout groups addressed four examples related to concentrated and connected infrastructure that all involved some element of the vulnerability of different critical infrastructure systems and issues associated with managing urban expansion (see Figure II-2).
  - A second set of breakout group discussions focused on specific cases related to the second integrative theme, drought and hydrologic variability (see Figure II-3).
  - A final set of breakout groups discussed several cross-cutting issues: framework vision; tools for modeling across multiple scales and sectors; and model evaluation, uncertainty characterization, and decision support. Discussion of data issues was integrated into several of these groups.

Detailed descriptions of the breakout group cases, assignments, and results are found in Appendix B.

Agency Example Uses: Concentrated and Connected Infrastructure	
	**1.1 Electric system reliability and demands affected by water quantity/quality |** Room 4102, Plenary ICG co-chair: Robert Vallario, U.S. Department of Energy SSG co-chair: Scott Backhaus, Los Alamos National Laboratory
	**1.2 Health services affected by cascading infrastructure failures and interdependencies |** Room 4056, Small Conference Room ICG co-chair: John Balbus, National Institutes of Health SSG co-chair: Christopher Barrett, Virginia Tech
	**1.3 Coastal city inundation affected by sea level rise and extreme weather events |** Room 4046, "Classroom" ICG co-chair: Charles Covel, U.S. Department of Homeland Security SSG co-chair: Ali Abbas, University of Southern California
	**1.4 Urban socioeconomic systems and vulnerable communities affected by heat waves and air-quality events |** Room 3502, JGCRI Third Floor ICG co-chair: Jia Li, U.S. Environmental Protection Agency SSG co-chair: Jennie Rice, Smarter Decisions, LLC

Figure II-2. Concentrated and connected infrastructure examples. Source: Workshop Program

Agency Example Uses: Drought and Increased Variability of Water Supply	
	**2.1 Reservoir resilience affected by droughts, floods, and changing extremes |** Room 4102, Plenary ICG co-chair: Kate White, U.S. Army Corps of Engineers SSG co-chair: Patrick Reed, Cornell University
	**2.2 State economies, including agriculture, affected by drought |** Room 4056, Small Conference Room ICG co-chair: Ronald Sands, U.S. Department of Agriculture, and Alexander Ruane, National Aeronautics and Space Administration SSG co-chair: Karen Fisher-Vanden, Pennsylvania State University
	**2.3 Planning for wildfire impacts and management under changing climate, environmental, demographic, and policy futures |** Room 4046, "Classroom" ICG co-chair: Linda Langner, U.S. Department of Agriculture Forest Service SSG co-chair: Claudia Tebaldi, National Center for Atmospheric Research
	**2.4 Surface-water quality and ecosystem services affected by droughts, floods, and changing land use/land cover trends |** Room 3502, JGCRI Third Floor ICG co-chair: Anne Grambsch, U.S. Environmental Protection Agency SSG co-chair: Ian Kraucunas, Pacific Northwest National Laboratory

Figure II-3. Drought and increased variability of water supply. Source: Workshop Program

III. Information needs and typology of uses

The examples of co-evolving interdependent systems explored at the workshop presented a sample of the varied planning decisions that users across the country face. Taken together, these kinds of decisions have important implications for the health, quality of life, economic vibrancy, and resilience of their communities, and the nation as a whole. While user needs are diverse and unique, there are also shared information requirements for commonly occurring challenges, for example, cost and reliability metrics for many types of infrastructure systems. This section of the report surveys the cases of co-evolving infrastructure, socioeconomic, and natural resource systems to identify shared information requirements as a first step in identifying the components of a modeling framework necessary to produce the types of information that could support users. This information can then be used to inform development of framework capabilities, for example, pointing to resolutions required for some common components such as information on extreme events, demographic trends, and location of critical infrastructure. Priority could then be given to developing model capabilities that can serve diverse uses.

III.1 Example information needs: investment and adaptive management

One set of cases discussed at the workshop focused on concentrated and connected infrastructure (a system), and the second on drought and hydrologic variability (a stressor). These cases involved two broad types of interrelated decision challenges: informing (1) investments in infrastructure systems and (2) adaptive management to increase preparedness. To explore requirements for the modeling framework and its component capabilities, the report now briefly summarizes some of the questions and information needs identified in the breakout group discussions (see Appendix B for detailed descriptions).

(1) Investment challenges: A key issue confronting a range of private- and public-sector decision makers is how will infrastructure investments over the next decade shape the vulnerability and resilience of communities over the next 50-100 years? Systems for electric power generation, water resources, cyber infrastructure, transportation, and other critical infrastructures are currently being engineered and financed. Developers need to consider how changes in supply and demand driven by socioeconomic trends and environmental change, including changes in weather patterns, could affect requirements for performance and the ultimate long-term economic viability of these systems. Without a better understanding of how different infrastructure configurations will interact with co-evolving socioeconomic, climate, and environmental systems, investments in this infrastructure could be under- or over-engineered, resulting in unmet demand or stranded assets. They could be at risk of underperforming or failing, with consequences for the economy, quality of life, the environment, and health and safety.

Investments in critical infrastructure for water and energy resources were discussed at the workshop. These are often considered independently, but the workshop focused on the interdependencies of these systems, even while recognizing that information needs for energy and water systems management have distinct requirements.

- Energy systems perspective: Investments are being made in resilient energy systems designed to meet future demand and achieve price and environmental objectives. These investments need to consider a rapidly changing energy sector that includes distributed resources as well as growing and shifting demands. What are the impacts on integrated infrastructure arising from changes in energy technology? What adaptation measures (operational rules, design, siting, importation, technology, institutional/regulatory, etc.) in the demand, supply, and transmission of electric power are most likely and viable for different regions to mitigate these vulnerabilities? A mix of chronic stressors (e.g., increasing demand, diversification or concentration of energy sources, groundwater depletion) and acute events (e.g., droughts, floods, heatwaves) will likely require inter- and intra-regional adaptation strategies that could interact with the stressors and each other over multiple time and spatial scales.
- Water systems perspective: Investments in water resources infrastructure, for example, reservoirs to manage both droughts and floods, are also underway. These investments need to consider interacting drivers and influences including climate-impacted hydrology, land use/cover change, changes in demand due to shifting patterns in management and use (e.g., increasing use of water for energy production), and changes in institutions and governance to balance competing needs. How would different configurations of water supply and handling infrastructure operate, given different scenarios of land use, population growth, and climate? How would different approaches to reservoir operations and the competing multi-sector demands that depend on them (e.g., hourly energy markets, daily municipal and industrial water use, flood risk reduction for storms on a daily timescale, seasonal agricultural or in-stream ecosystem flow allocations, decadal shifts in urban water demands, etc.) affect the needs for infrastructure to manage increasingly extreme floods and droughts?

(2) Adaptive management seeks to balance interacting stresses of weather, climate, land use, sea-level change, and socioeconomic factors to avoid loss of productivity, service interruptions, and increased morbidity and mortality. It enables managers and decision makers to respond to changing conditions and adjust future plans accordingly by maintaining flexibility. How will changes in migration patterns, demographic characteristics, the location of vulnerable populations, livelihoods, and other factors interact with altered environments and weather patterns that affect the location, intensity, duration, and frequency of floods and other events? What is the potential to reduce these risks through retrofits, operational

strategies, creation of redundant systems, land use planning, and design of strategies for disaster management and recovery? Some of the specific examples discussed included:

- How vulnerable are different urban and rural communities to *large-scale coastal and inland flooding?* Such events result in deaths, injuries, and illness, as well as billions of dollars of property damage and long-term disruptions to affected communities. This is not just a challenge for coastal cities but also for inland urban and rural areas, as witnessed by the string of dramatic flooding events in 2016 alone in West Virginia, Texas, Oklahoma, South Carolina and Louisiana. How can planners and responders most effectively improve their ability to mitigate flooding events and manage those that are unavoidable? What are the climate/weather thresholds for flooding under different infrastructure/design scenarios?
- What is the potential for *wildfires to destroy housing and communities at the wildland-urban interface*? Depending on the uncertain future evolution of regional climate and societal factors, how will the ensuing changes in wildfire extent and severity impact the provision of ecosystem services from forests and rangelands, and human health and infrastructure? What adaptation measures have the greatest potential for reducing risks and impacts from wildfires? For example, how can zoning and building standards reduce the potential for losses?
- What is the potential for *cascading failures across critical systems* stressed by high demands resulting from population growth, shifts in use, and extreme events such as heat waves that spike demand beyond engineered performance standards? Planners could benefit from projections that show how incidence and severity of these events will evolve with underlying changes to demographics, weather/climate, and the systems themselves. How could alternative urban designs and infrastructure configurations affect the propensity for failure and need for emergency services?
- How could *interrupted access to and failure of healthcare services* caused by cascading infrastructure failures affect public health? The challenges are affected not only by the probabilities of cascading systems failures, but also by the ability of healthcare facilities to access backup sources of energy, transportation, water, and communications. Another key issue is the epidemiologic risk assessment of the health burden, both from the event itself as well as the ongoing needs for healthcare. Studies seldom address the unique vulnerabilities of healthcare facilities in any detail. What are the health implications when linked health systems in an urban area lose critical infrastructure during one or a series of extreme weather events?
- What are the *potential challenges for air-quality management and public health* under different technology, economic development, and climate scenarios? The stage for urban air-quality issues is set by factors involving complex interactions among population growth, land use change, urbanization (and associated “heat islands”), infrastructure development, and economic activities. Interactions of these trends with co-occurring pollutant emissions, heat waves, and elevated levels of allergens (molds, pollen, etc.) can increase morbidity and mortality from cardio-respiratory diseases, as well as limit outdoor activities and economic productivity. How might land use planning, transportation system planning, and other approaches reduce health vulnerabilities from changing weather patterns and air pollution in urban areas?

III.2 Toward a typology of use and framework capabilities

At the workshop, participants considered how to categorize the information needs of different user groups, and to identify combinations of data, models, and other capabilities that would be useful for producing the needed information on specific variables at the required spatiotemporal scales. The objective was to consider what capabilities were needed in the framework and to identify groups of users who could provide input to formulating research objectives and plans.

A typology of use is defined by both the technical requirements for modeling as well as needs for decision support. For example, some of the characteristics of the problems discussed in the workshop (such as metrics used to test hypotheses or decision criteria used to evaluate decision options) would affect the range of models and types of coupling required to produce information on trends, relationships among variables, and relevant outcomes. Other characteristics (such as how often the decision was made, whether users wanted simple models they could employ to evaluate scenarios or more complex analysis produced by modelers) would determine factors such as the types of analysis/interpretation methods, use of scenarios or other methods for bounding uncertainty, visualization, and other approaches for ensuring effective communication, learning, and preference formation.

Table III-1 illustrates an example use typology, including metrics, drivers/uncertainties, and decision alternatives associated with different user perspectives for one of the cases (reservoir resilience affected by drought/extremes), as well as preliminary ideas about the implications of these aspects of information needs for temporal and spatial scales, and the model coupling approaches required.

Table III-1. Typology of use for reservoir resilience affected by drought/extremes: Illustration of information requirements and implications for the characteristics of needed models/methods for an example problem considered in the workshop.

Typology Field	Examples
User Perspective	Water planners and engineers at state/city scales; water system owners/operators
Key Parameters/ Metrics	Resilience (recovery time); robustness (reliability); costs/regrets/benefits of operations/resource allocations; trade-offs in economic and engineering performance measures
Drivers/ Uncertainties	Climate-impacted hydrology; changing land use; water demand management; renewable energy use; demographic/socioeconomic impacts on demand; dietary preference and agricultural demand; resource management polices; institutional effectiveness
Alternatives under consideration	Change in operations/resource allocations; investments in infrastructure; land use policy; demand management programs
Temporal Resolution/Scale	Daily (hourly?) for hydrology; annual for changes in terrestrial systems; IAM time step for agricultural demand affected by climate and socioeconomics
High-resolution, basin-scale hydrology;	High-resolution, basin-scale hydrology; political units for global trade
Models/Couplings	Soft coupling and/or use of emulators for some factors influencing water demand (e.g., global agriculture prices)

The breakout groups were not assigned to identify all possible information needs related to their issue, but rather to define a single or small number of related user perspectives that would enable them to identify specific decision criteria or other metrics that would need to be produced by a specific configuration of models and other capabilities. Each group selected a user perspective as a lens for examining the problem, as opposed to identifying the full range of users with a stake in the problem. This use perspective was then the focus of their efforts to identify needed data, models, types of coupling, analysis methods, and other potential components of the multi-sector/scale modeling framework.

Looking across the examples of co-evolving systems and information needs, the groups identified cases at a wide range of spatial scales and decision-maker types. Table III-2 presents the uses/users identified for each of the specific cases discussed at the workshop. These span a range of governance levels and sectoral perspectives, from national to local, including government and private-sector actors. As expected given the breadth of sectors covered by the illustrative examples, a wide range of issues across interacting land-energy-water systems is included.

Table III-2. Uses/users identified by each breakout group

	Concentrated/Connected Infrastructure				Drought/Increased Hydrologic Variability			
	1.1 Energy	1.2 Health	1.3 Coastal inundation	1.4 Urban heat/air quality	2.1 Reservoir resilience	2.2 State economies focused on agriculture affected by drought	2.3 Wildfire impacts and management	2.4 Surface water-quality and ecosystem services
National		HHS disaster preparedness and climate adaptation		Air-quality and health managers		USDA specific agencies (conservation and emergency)	Federal forestry and wildfire managers; emergency managers; air-quality managers	Water-quality managers; ag and conservation program managers
Regional	Regional utility commission			Air-quality managers				
State		State health Departments	State planners/land use managers	State air-quality and health managers	Planners/ engineers	State agriculture agencies	State forestry agencies	Water-quality and land use managers
Local		Local health Departments	City planners/ land use managers	Planners, emergency responders	Emergency managers		Local governments; emergency/ fire fighting	
Private Sector	Regional utility system operator	Regional healthcare coalitions	Infrastructure owners and operators		Owners/operators of water resources infrastructure		Forest/rangeland and commercial/ residential property owners	Reservoir operators

Table III-3 builds on this summary of the actors involved in the cases and considers a hierarchy of uses across spatial/temporal/governance scales. A number of these uses are closely tied to classes of investment and adaptive management decisions: These include (1) planning future infrastructure requirements, (2&3) planning future emergency response/public health needs, (4) urban/regional planning for future populations and stresses, (5) regional utility planning, and (6) state economic development. Additional uses are related to research and development: (7) analyzing technology performance gaps and future R&D needs, (8) analysis of institutional effectiveness (e.g., standards and codes), and (9) basic research on multi-scale dynamics. The table begins to analyze required capabilities in terms of temporal and spatial resolutions. Some of these uses require mixing temporal resolutions from hourly (and even shorter) timescales at very high spatial resolution (less than 1 km for some types of infrastructure network models) with more aggregated representations (e.g., ~20 or so world regions on annual or longer time steps) of changes in demand that result from evolution of population size and location, trade patterns, and other global-scale processes. A challenge is that for most applications, high-resolution information is required over multiple years and decades to identify changes in variables such as peak loads, maximum or minimum temperatures, and the intensity-frequency-duration of precipitation or other extreme events. Needs for information about institutions occurs at all governance/spatial scales and must consider the interactions of policies, markets, and factors such as changing preferences over time. Managing the diversity of topics addressed and temporal and spatial resolutions required require further analysis and development of a hierarchy of information needs and capabilities. As discussed at the workshop, the diversity of required capabilities raises multiple methodological and analytical issues. For example, what approaches are available for representing complex interactions across infrastructure systems with aggregate data such as statistics of system performance under different scenarios? How can losses in fidelity in aggregate representations be balanced with computational, data, and other requirements of representing systems at high resolution? What approaches are available for discovering innovative adaptive management approaches that leverage complex interactions across infrastructure systems?

Many workshop participants considered continuing to develop the concept of a use typology to be a priority. Options for further research and analysis include collecting additional data on specific decision criteria and information needs, further analysis of flows of information across system components, spatial/temporal scales, and governance levels, and identification of existing capabilities and gaps in components required to provide the information needed to address key science and decision-support questions. A particularly interesting area for investigation concerns the common information needs associated with managing infrastructure systems (which require tools to represent these systems at high resolution and frequency) in the context of higher-order systems that operate at low resolution and frequency.

Table III-3. Hierarchy of information needs and temporal/spatial resolutions

	Hypothetical use perspective	Objective/ information needs	Temporal resolutions	Spatial resolutions
Infrastructure and Investment	1. Future infrastructure requirements/ Planning	Characteristics of resilient systems in context of multiple stresses and socioeconomic change	▶ Hourly for infrastructure performance ▶ Statistical (IDF) for climate stresses over decades ▶ Annual or longer for socioeconomics	▶ H for infrastructure and stresses ▶ Regional to national for socioeconomics (in some cases for global system)
	2. Planning emergency response	Confluence of vulnerable populations, extreme events, systems disturbance due to threshold exceedance	▶ Hourly/daily for extremes and systems disturbance over decades; ▶ Annual to decadal for infrastructure performance and population characteristics	▶ L for long-term demographic trends ▶ H for spatial distribution of vulnerable populations
	3. Public health planning	Co-location of environmental epidemiology of vulnerable populations, extreme events, infrastructure/health systems prone to interruptions, decision-making influences and patterns	▶ Hourly/daily for extremes and infrastructure disturbance over decades; ▶ Annual to decadal for system vulnerability and population characteristics	▶ L for long-term demographic trends ▶ H for spatial distribution of vulnerable populations ▶ H for urban and health infrastructure ▶ H for vectors
	4. Urban/ regional planning	Regional population distribution (e.g., urban/rural) and quality of life as affected by co-evolving infrastructure, socioeconomic trends, extreme events, natural resources	▶ Hourly/daily for extremes and infrastructure disturbance over decades; ▶ Annual to decadal for urban geography and population characteristics	▶ L for long-term demographic trends ▶ H for spatial distribution of vulnerable populations ▶ H for urban infrastructure
	5. Regional utility planning	Combination of interests for (1) infrastructure planning and (4) urban/ regional planning	▶ Hourly for infrastructure performance ▶ Statistical (IDF) for climate stresses over decades ▶ Annual or longer for socioeconomics	▶ H for infrastructure and stresses ▶ Regional to national for socioeconomics (in some cases for global system)
	6. State economic development authority	Resiliency of economy, migration as affected by co-evolution of infrastructure, socioeconomic trends, extreme events, natural resources (similar to (4))	▶ Statistical representation of infrastructure failures ▶ Seasonal to annual for evolution of bio-economy supply/demand/production ▶ Annual to decadal for socioeconomics	▶ County scale for bio-economy information? ▶ H for land use and infrastructure ▶ State to national for broader socioeconomic trends
Research and Development	7. Technology -specific research and development (e.g., chief technology officer)	Gaps in performance of current infrastructure systems and technologies relative to future conditions (similar to (1)), evolving demands relative to global trends in supply/demand/markets of key resources, service, goods	▶ Statistics of infrastructure performance, climate stress at high frequency; ▶ Annual or longer for global trends in markets ▶ Decadal for evolution of technology cost/performance characteristics	▶ H for sample/typical infrastructure system and example stresses ▶ Regional to national for socioeconomics (in some cases for global system)
	8. Research on institutions/policy effectiveness (e.g., Federal managers)	Demands and performance for infrastructure, environmental systems, cost-benefit analysis of institutions/policies, place-based dynamics that affect attainment of management objectives	▶ Statistical representation of infrastructure system performance under varying conditions ▶ Annual or longer for evolution of supply, demand ▶ Annual or longer for broader socioeconomic development pathways including evolution in institutions	▶ H for sample/typical infrastructure system and example stresses ▶ Regional to national for socioeconomics (in some cases for global system) ▶ Local to national for institutional representation
	9. Basic research, e.g., multi-scale dynamics, co-evolution of complex systems	All of the above with emphasis on cross-scale interactions from infrastructure operations (1) to regulatory/institutional questions (8)	▶ All of the above	▶ All of the above

IV. Framework objectives and potential conceptual structures

Based on the preliminary analysis of information needs in Section III, we now consider some of the driving scientific questions and objectives that a framework for modeling and analysis of complex infrastructure, natural resources, and socioeconomic systems could be used to address.

IV.1 Scientific questions

An important step in designing this framework for data, modeling, and analysis is to articulate science questions to guide development of capabilities. Formulating a comprehensive research agenda is beyond the scope of this report because that was not one of the objectives of the workshop, but here we highlight some of the questions raised during the sessions to indicate possible elements of that agenda. We consider questions associated with the framework as a whole (such as those arising from complex systems theory), as well as questions specific to research on integrated assessment, impacts/adaptation/vulnerability, and Earth systems.

One commonly occurring question across the different cases concerns the ways in which the distribution and characteristics of population groups across the landscape will affect the location of infrastructure, and vice versa, and how both these evolutionary processes are affected by changes in weather extremes and other environmental impacts. How have populations, infrastructure, and environmental change processes interacted in the past? Can instances of co-evolution of these systems be identified and projected? What is the role of the demographics (e.g., age structure) and factors such as governance in influencing migration in response to or anticipation of environmental impacts and change? As discussed in many of the cases, another common issue is interactions and feedbacks among different types of impacts, and feedbacks of these impacts onto Earth system processes. What are the risks for cascading failures across systems for different configurations of infrastructure, environmental, and socioeconomic systems? Can spatial or other patterns of overlapping impacts and dependencies be identified for different geographic regions of the United States? A related practically oriented but scientifically challenging question is what opportunities exist to reduce tight coupling and feedbacks among systems in order to enhance the ability of infrastructure systems to withstand and recover from disruptions? Another example science question is the potential for co-occurrence of natural and human-caused stresses that could fundamentally alter the evolutionary processes in play in these systems. Finally, a fundamental question raised by complex systems theory is highly relevant: what are the opportunities for and limits to human control of such systems? This question seems particularly germane when considering the potential for randomly co-occurring extreme events and shocks to lead to unexpected interactions and cascading systems failures.

Earth systems, IAV, and IA research have well defined scientific agendas that focus on improving understanding of basic processes and critical uncertainties within their disciplinary domains. We build on these agendas and focus here on the subset of issues and questions raised during the workshop that must be addressed to improve understanding of the ways that Earth systems, impacts, and broader socioeconomic forces intersect and co-evolve, with implications for resilience. Some of the key cross-cutting questions from these established areas of research include:

Earth systems science questions

- How will the intensity, duration, and frequency of a variety of extreme events change in response to changes in mean conditions and different patterns of forcing (including changes in land use/cover)?
- What are the potential feedbacks on local climate and physical systems (e.g., hydrology, vegetation) of different adaptation and mitigation strategies?

- What feedbacks (e.g., forest dieback, methane release from frozen soils) could lead to thresholds that produce abrupt changes in climate?
- What methods are available to efficiently characterize uncertainty in future climate patterns at different time and spatial scales for use in multi-scale and multi–sector modeling studies and decision support?
- Which aspects of climate change are most important to characterize, at what spatial and temporal scales, to understand potential impacts on important resources and technology systems?

Impacts, adaptation, and vulnerability science questions

- What impacts on the energy-water-land system can be expected considering changes in both mean state and extreme events?
- What is the potential for abrupt impacts and tipping points in key areas such as ice-sheet dynamics/sea-level rise or changes in pests and other disturbances of ecosystems leading to massive dieback?
- What is the relative importance of different stressors including changes in land use/cover and a wide range of socioeconomic conditions that affect vulnerability in producing observed impacts?
- What are the influences of global and national trends and aggregate impacts (e.g., prices, wages, demands for goods/services, productivity) on local vulnerability and resilience?
- What adaptation options are available, and how well will they perform under different configurations of infrastructure, assumptions of socioeconomic development, different institutional constraints, and varied climate and environmental conditions?
- How will different institutional and systems constraints (e.g., operating rules, market mechanisms, reserve requirements) affect impacts and vulnerability at scales from local to national?
- Which aspects of institutions and social processes need better representation in IAV models to understand impacts, vulnerability, and resilience? How should evolution of institution and social processes in response to impacts be represented to understand the dynamic process of responses?
- What formal analytic methods can be developed to discover innovative adaptation options that span multiple sectors and require input from multiple decision-making or regulatory bodies?
- How can information on potential impacts be presented to provide insight to decision makers, given pervasive and deep uncertainty that can seem to render any results unusable?

Integrated assessment and broader socioeconomic process questions

- What are the most significant pathways and processes that will aggregate local-scale impacts and affect large-scale critical infrastructure systems and regional-to-global socioeconomic institutions and processes? For example, how will changes in climate and their impacts affect migration, patterns of economic development, and natural resources, and how will these in turn affect regional and national development pathways?
- What teleconnections exist between local-scale impacts in different regions of the U.S. and different countries and global regions?
- Which critical infrastructure networks and economic sectors seem most at risk of instability or failure resulting from the aggregation of impacts across multiple locations?
- How can IA modeling and research better represent complex systems processes using spatiotemporal averaging and other reduced-form representations that facilitate analysis of uncertainty?

Progress in addressing such questions will require progress on a set of cross-cutting methodological challenges. These include developing an overall conceptual framework that bounds the systems, identifies constituent subsystems, and defines required levels of detail, complexity, and spatiotemporal resolution for specific questions.

An initial methodological challenge is to test the hypothesis that feedbacks across systems are significant enough to require developing integrated models. The norm in IAV research has primarily been to use models of *individual* sectors to consider the potential effects of future climate change. But emerging research discussed at the workshop and related meetings (e.g., Harrison et al. 2016) points to the importance of including cross-sectoral and cross-scale interactions in impacts modeling. This study used an integrated assessment platform to explore differences in model results of indicators of impacts across several land-based systems in Europe (agriculture, water resources, forestry, etc.) when single-sector and more complex integrated models are used. Figure IV-1 illustrates that an integrated approach yields significantly different results—differences of up to 25 percent in modeled impacts indicators when comparing single-sector analyses to results from an integrated model that accounts for feedbacks and interdependencies. The study authors evaluated the results using published impacts assessments. Considering the interactions across different domains raises the challenge of deciding which processes are endogenous and exogenous to different component models, and adopting a consistent approach so that information can be transferred effectively across components. Addressing challenges such as this is essential to building on improvements in framework components to advance skill in modeling the complex system.

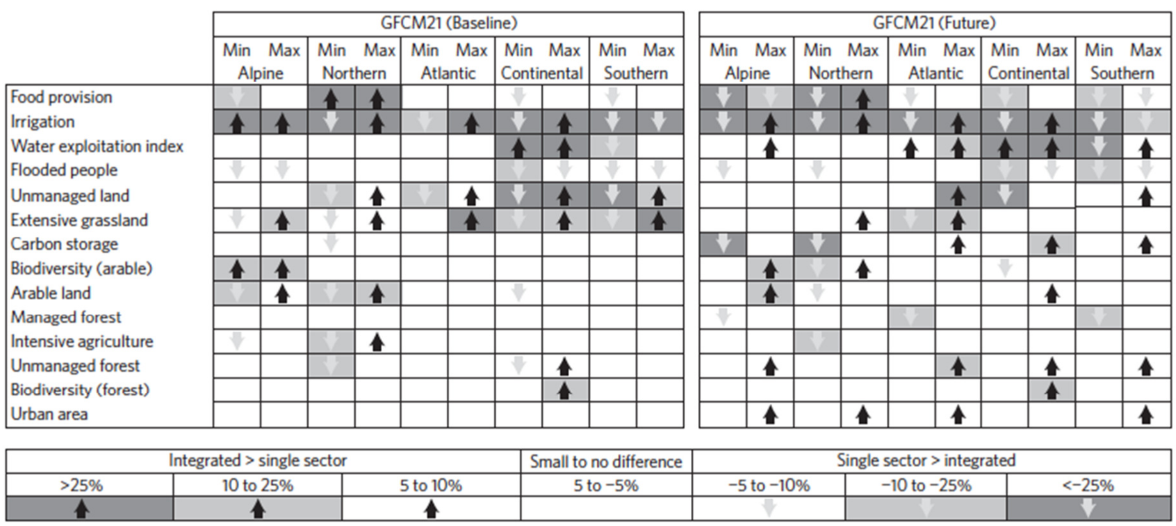


Figure IV-1. Summary of results from a European-based study that compares results for specific impact metrics using individual sectoral models and an integrated assessment platform that incorporates feedbacks across systems. Results indicate positive and negative differences exceeding 25 percent for some metrics and imply the need to develop better representation of these feedbacks and interdependencies in modeling.

Another methodological challenge is to determine what level of complexity and resolution is needed to address different scientific and applied questions. When are more complex, highly resolved representations needed, and when will simpler formulations of more aggregate variables suffice to study the co-evolution and characteristics of these complex systems? When are the feedbacks and interactions across systems sufficiently important that more complex, integrated approaches are required? Continuing to improve our understanding of the types of problems and science questions that benefit from incorporating cross-sector and cross-scale interactions, and how best to represent these interactions in a modeling framework, is a core scientific challenge.

In plenary discussions and many of the breakout groups, the issue of the appropriate level of spatial/temporal detail of models was noted. Some of the relevant IAMs that would be used to provide information on prices and demand for different commodities as well as information on land use/cover change and emissions of climate forcers operate at highly aggregated scales, for example, resolving on the order of 10-30 global regions. In contrast, models of infrastructure networks (e.g., electric power, natural gas, water distribution) include approaches that resolve the dynamic physics of a network down to the scale of individual network components. There are numerous challenges to matching scales/resolution, determining what information is needed in a particular case, and developing simplifications and reduced-form models that still provide accurate representations of a system's operation. What approaches are effective for using reduced forms or spatiotemporal averaging to represent in a coupled model system the properties of the systems whose operations are affected by detailed characteristics of their configuration? What is lost in terms of model fidelity that would affect the quality of information passed to other models? Figure IV-2 illustrates some of the complexity and scale challenges.

Figure IV-2. Range of scales: Many infrastructure networks span a wide range of scales including national, regional, local and facility specific. For typical utility planning processes, simple aggregation of fine-scale networks may be sufficient to accurately predict behavior at larger scales, e.g., aggregating electrical distribution grid load to estimate load on transmission network nodes in a regional transmission system. For other processes, such aggregation may be insufficient and misguide decisions. The resilience of a distribution network to damage from hurricanes may be spatially heterogeneous (e.g., because parts of that network serve critical facilities and have already been hardened). Ignoring these fine-scale correlations in system hardening investments when spatially aggregating will lead to inaccurate models at coarser scales. Source: Scott Backhaus, LANL.

IV.2 Overarching objectives and challenges

Understanding the dynamics of the co-evolving systems discussed at the workshop and addressing the science questions described above will require a collection of different models and framework capabilities that enable researchers to configure data and models into different use-inspired instantiations. This is because no single "über model" would be able to incorporate all of the different processes and feedbacks at the widely varying temporal and spatial scales required and still remain a tractable platform for analysis. A single model with a fixed configuration of all the potentially relevant systems would be unworkable from the perspectives of data requirements, set up, computational requirements, and uncertainty characterization, as well as other requirements.

Considering the scientific questions and the examples of co-evolving interdependent systems discussed throughout the workshop, participants identified a possible overarching objective of the framework to

- "Develop an interconnected system of models, data, analysis, and decision-support capabilities that help build resilience in interdependent systems".

The agency program managers, SSG members, and workshop participants stressed the potential societal relevance of the modeling framework. Considering the need to guide scientific progress so that it results in usable knowledge, participants formulated a "grand challenge" that the research and user communities work together to develop the framework.

While these are plausible ideas for objectives and a development process, formulation of a specific vision and objective for the framework would require additional shaping by the agencies. A better-defined vision and objective needs to balance specific scientific and decision-support objectives and focus on the key information needs identified by stakeholders, whether scientific or end users.

IV.3 "Framework" defined: an agile environment for modeling and learning

A question that was addressed in many of the conversations during the workshop was what was meant by the term "framework". No effort was made to reach a consensus, and disparate viewpoints were expressed. Beyond a nearly universal sense that the term does not imply a single model with fixed components and configurations, a number of key characteristics or components of a framework were identified. In simplest terms, the idea is to provide a learning and modeling environment in which researchers can identify and select data and models from a larger collection of resources and integrate them to study complex problems that involve interactions of processes represented by the individual models. To meet this simple objective, the framework needs to incorporate a modular, interoperable, and agile approach to link specialized data sets and models of relevant systems spanning climate, critical infrastructure systems, natural resources, agro-forestry, and socioeconomic systems. It needs to be able to accommodate interactions of these many processes and subsystems across geographies and time scales. The conceptual structure needs to define system boundaries and subsystems, and to clarify the relationships and information flows across a hierarchy of models and spatial/temporal scales. Data and models relevant to the wide range of different processes and systems considered here can be expected to differ in important respects, including time and spatial scales, variable names and units, programming languages, and other characteristics. Thus the framework will need to provide a variety of tools for reconciling differences that would otherwise prevent exchange of information across component models, data sets, and analysis methods.

Specifically, a useful framework was identified as having these sorts of characteristics and capabilities:

- *An overall conceptual structure* for planning integration of different areas of science and organizing data, models, and other capabilities;
- *A typology of use* that organizes the information requirements for different types of science and use-inspired analyses, and the capabilities required to produce needed information;
- *An analytic process and methods to identify components needed* for a given scientific question and/or application;
- *A diverse range of capabilities* to represent the drivers, decision variables, processes, and uncertainties in the cases, including both detailed and reduced-form representations of multiple types of models of the relevant interacting systems;
- *Shared naming conventions/vocabulary* (taxonomy) for processes, variables, units, and types of coupling to facilitate efficient and accurate sharing of information;

- *Metadata on data, models, and analysis methods* so that users can differentiate functionally similar capabilities that vary in specific characteristics to determine which ones are best suited for their needs;
- *Sophisticated provenance management* to capture all modeling choices, input and output data sets, coupling strategies, and so on, for particular instantiations of the framework;
- *Evaluated coupling strategies* for bringing together models across domains, resolutions, and levels of complexity;
- *A software environment* for the many different types of coupling required to pass the required information across the modeling domains;
- *Methods and tools for model evaluation and analysis of uncertainty* of both individual and coupled components;
- *Formal methods for decision support* that enable discovery of non-intuitive adaptation methods that span multiple sectors, scales, and models and support practical applications;
- *Visualization methods* to enable decision makers to understand and evaluate the complex interactions and adaptation pathways;
- *Community-building components* such as coordinated experiments, intercomparison activities, a wiki or other method for sharing information about capabilities as they are developed, etc.

Not all of these aspects would be needed for any single case. Rather this is the set of qualities that a framework would need to have to facilitate development of a community of practice to advance this research agenda.

IV.4 Clarifying needs for "coupling"

A challenge in creating the framework for data, modeling, and analysis is to understand the required flows of information among subsystems, and to manage these flows in ways that are computationally efficient and facilitate analysis of uncertainty.

Looking back to the examples of co-evolving systems discussed at the workshop, there are many different types of interconnections across sectors, space and time scales, and governance levels, and thus different types of coupling mechanisms that would need to be created:

- *There is the potential for one system to affect the operation of others through feedbacks and impact cascades across tightly connected systems*. This establishes a requirement to couple models that represent these systems to understand the potential for systems failure under multiple interacting stresses, for cases where this is an issue.
- *Impacts and trends at local scales can accumulate and have impacts on national and global systems and trends*. Thus modeling needs to represent interactions of impacts across locations, and to aggregate impacts to regional, national, or global economic trends and flows of goods and services, for example, to estimate how production shortfalls (or surpluses) of commodities (e.g., agriculture, energy) in one location can interact with those at other locations and impact the national or global economy.
- *Changes at the national to international level could have feedbacks on infrastructure and systems at local scales through factors such as migration, prices, and dependence upon flows of resources and services*. Thus it is necessary to be able to represent evolving macro-level trends in demography, economic development, and the vulnerability of different population groups in the context of global

and national trends, and to connect these aggregate trends to the evolution over time of highly resolved and complex models of infrastructure and natural systems.

These interactions create the need for multiple coupling approaches and even raise a fundamental issue about the meaning of the term "coupling." The term was used by different participants to mean very different ways of passing information from one model to another. In some cases, people referred simply to one-way, one-time flows, for example, the transfer of climate information to an impacts model. This type of information flow is adequate for an instance in which one system influences another and there are no feedbacks. In other cases, participants limited their use of the term to bi-directional transfers of information, for example, when climate change induces alterations in land use/cover that then have impacts on local-to-regional climate. Decisions about how to couple models need to consider the nature of the interaction of different sectors or scales including what the influences are, the directionality of the flow of influence, and the time steps at which the feedbacks occur. These then determine decisions about what information needs to be passed between models, whether two-way feedbacks need to be incorporated, and how frequently.

The May workshop did not systematically address this issue, although it was clear from discussion that clarification was needed. Defining different types of coupling was discussed at a subsequent workshop convened to explore the state of science in coupling integrated assessment, impacts, and Earth system models.[2] Participants at this second workshop considered alternative approaches for describing model coupling along several dimensions, including the extent and frequency of interactions, and the degree of software integration required (see Figure IV-3).

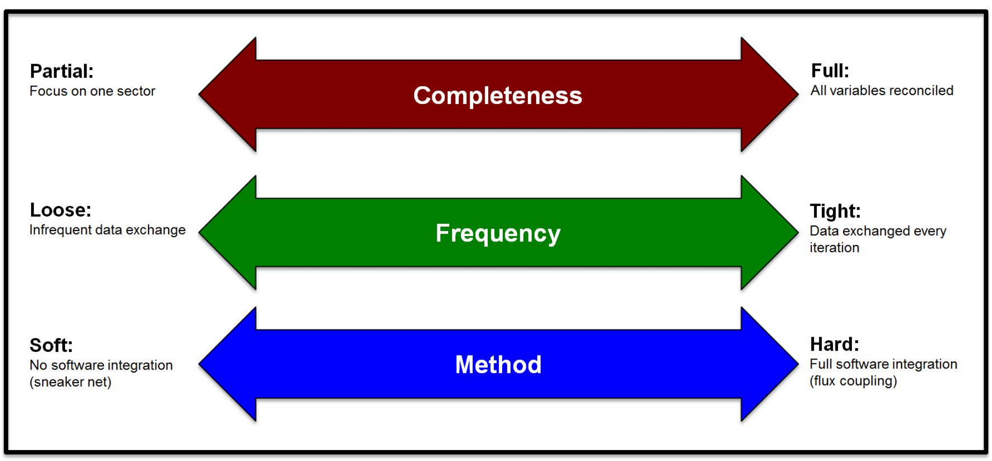


Figure IV-3. A spectrum of coupling approaches representing the need to reconcile variables, the frequency at which information is passed among component models, and the degree of software integration required. Source: Katherine Calvin, PNNL.

A final important point related to "coupling" is that translational tools and coupling software are an important area that requires additional research. Development of a framework hinges on the ability to connect component models/data, which is challenging for many epistemological and technical reasons. Some of these issues are addressed below, in Section V (Implications for framework capabilities).

[2] Calvin, K. Fisher-Vanden, K., Moss, R.H. and J. Weyant (Forthcoming). *Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus: Workshop Report.* Energy Modeling Forum Climate Change Impacts and Integrated Assessment Workshop XXII. Colorado, United States (July 25-29, 2016).

IV.5 Candidate conceptual structures

Several different approaches were discussed at the workshop for creating an overall conceptual structure for the framework to help bound the complex system, define and bound constituent subsystems, and identify needs for data, models, and other capabilities to represent and analyze interactions and systems behavior. One approach focused on considering interactions across systems and scales including large-scale Earth systems processes, fine-scale climate data translation, the dynamics of physical and socioeconomic systems (both independent of and as affected by climate change), and detailed models of socioeconomic sectors. The framework defined in this fashion organizes the effects/feedbacks and flows of information among these systems (see Figure IV-4).

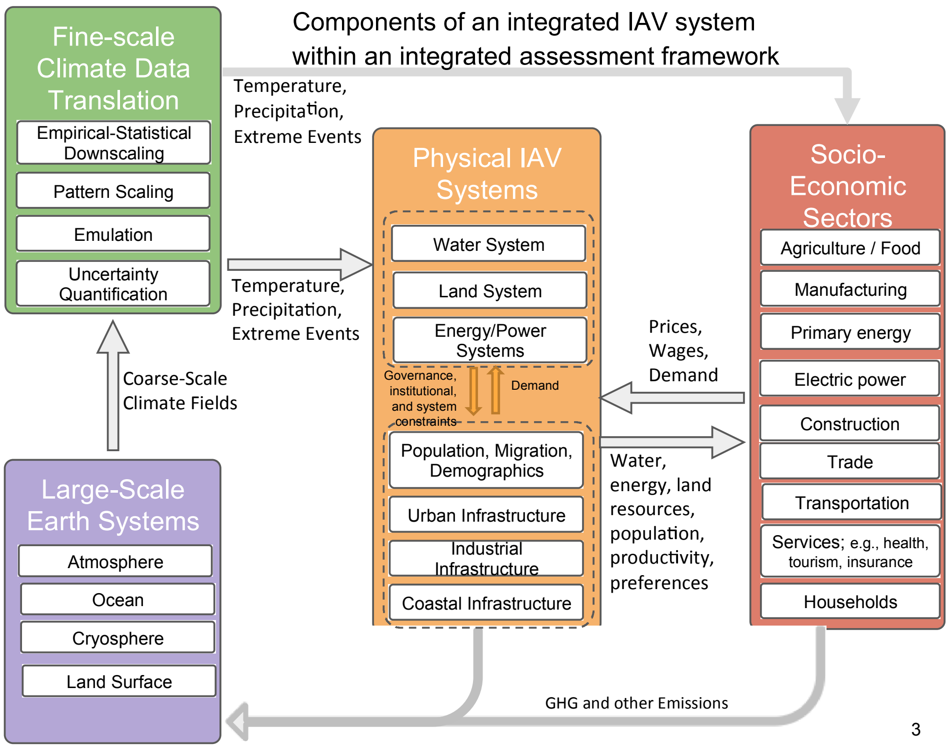


Figure IV-4. Interactions and flows of information across major components and systems at the IAV-IA-ES interface. Source: Karen Fisher-Vanden and Robert Nicholas (Pennsylvania State University), and Robert Vallario (U.S. DOE).

Figure IV-4 shows how the various components of a multi-model, multi-scale IA-IAV framework are interlinked. As shown in the figure, downscaled regional climate data in the form of temperature, precipitation, and extreme events are inputs to the structural IAV models representing the water system, land (including agricultural) system, energy/power system, population/migration/demographics, and urban/industrial/coastal infrastructure. Governance, institutional, and system constraints are captured in these structural IAV models. An IAM, capturing the socio-economic sectors, will provide the linkages between the structural IAV models. Changes to the physical system (water, energy, land, resources, population, crop yields/productivity, preferences) that are estimated by the structural IAV models as a result of changes in climate are fed into the IAM, which leads to changes in goods prices, wages, and demand for goods and services. These economic variables are fed back into the structural IAV models to capture economic feedbacks that can further alter the physical systems. By linking the IAV models through the IAM, we are able to model integrated impacts—i.e., how individual sectoral impacts affect other sectors through prices and demand.

A second approach presented at the workshop has conceptual similarities but parses the systems slightly differently. This conceptual structure includes some of the same elements, namely, the regional Earth system, individual sectors, and an integrated assessment model. The regional climate component is driven by boundary conditions provided by a Global Climate Model, which in turn is driven by a global scenario that includes socioeconomic factors that provide the broader context in which the sectors operate (e.g., global trade patterns in commodities, prices for resources such as energy and food, etc.). Also notable is that the coupling options (i.e., models included and how they are linked) and uncertainty characterization employed in any particular application of the framework will be driven by the question being addressed. See Figure IV-5.

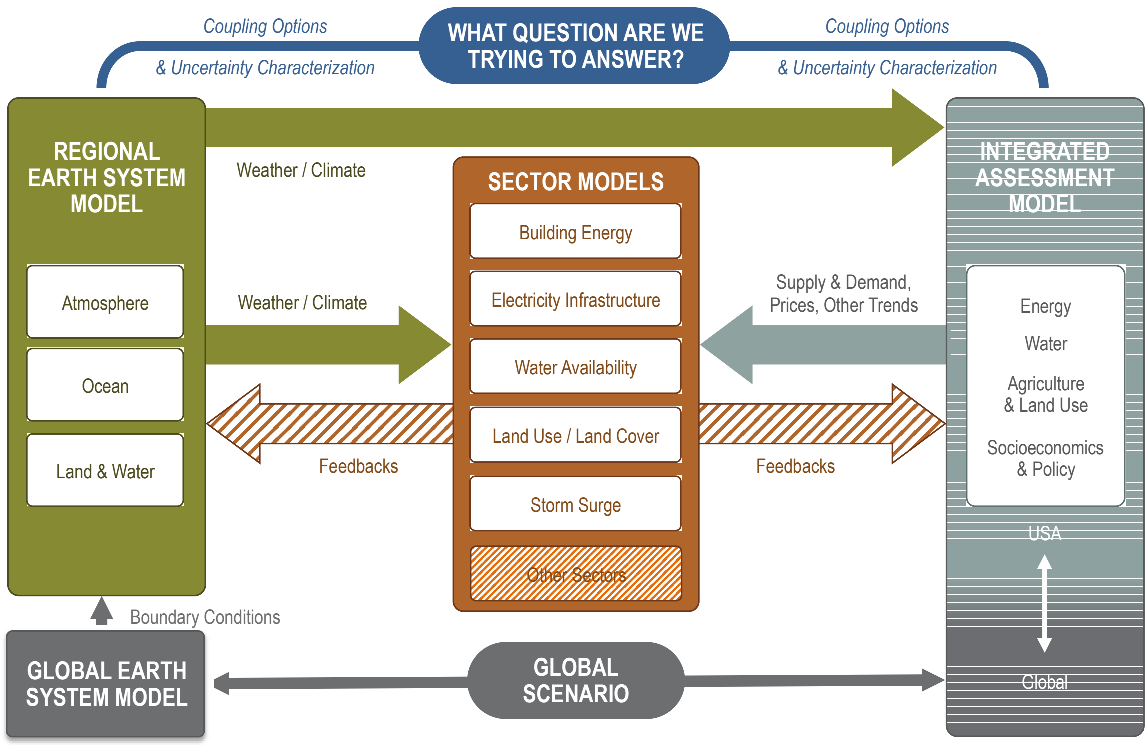


Figure IV-5. Source: Adapted from Kraucunas, I., Clarke, L., Dirks, J., Hathaway, J., Hejazi, M., Hibbard, K.,... & Leung, R. (2015). Investigating the Nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Climatic Change, 129(3-4), 573-588.

Participants at the workshop discussed these as examples of frameworks that incorporated some of the relationships among subsystems. Multiple perspectives were expressed about alternative conceptual approaches reflecting the different disciplinary background of participants. A key issue is determining which processes are endogenous or exogenous to different framework components, which affects choices of how to effectively integrate knowledge across different disciplines. Many ongoing modeling activities across the research community are including different representations of the same processes, and as these models are linked, the potential exists that a single process is being represented in more than one place in a chain of models, which could affect validity of the model results.

A cross-cutting breakout group was asked to explore an integrated vision and concept for the framework in light of discussion at the workshop. This group proposed an approach that integrated human, natural, and climate system elements to address scientific and decision-support challenges (see Figure IV-6). The conceptual structure focuses on integration of information on system inputs, detailed processes, and system responses through an integrating mechanism that plays the role of a "flux coupler", aggregating state variable responses across processes and time scales, to calculate output metrics. It supports forward simulation of adaptation decisions and can provide inputs to formal methods of decision support in a complex modeling environment.

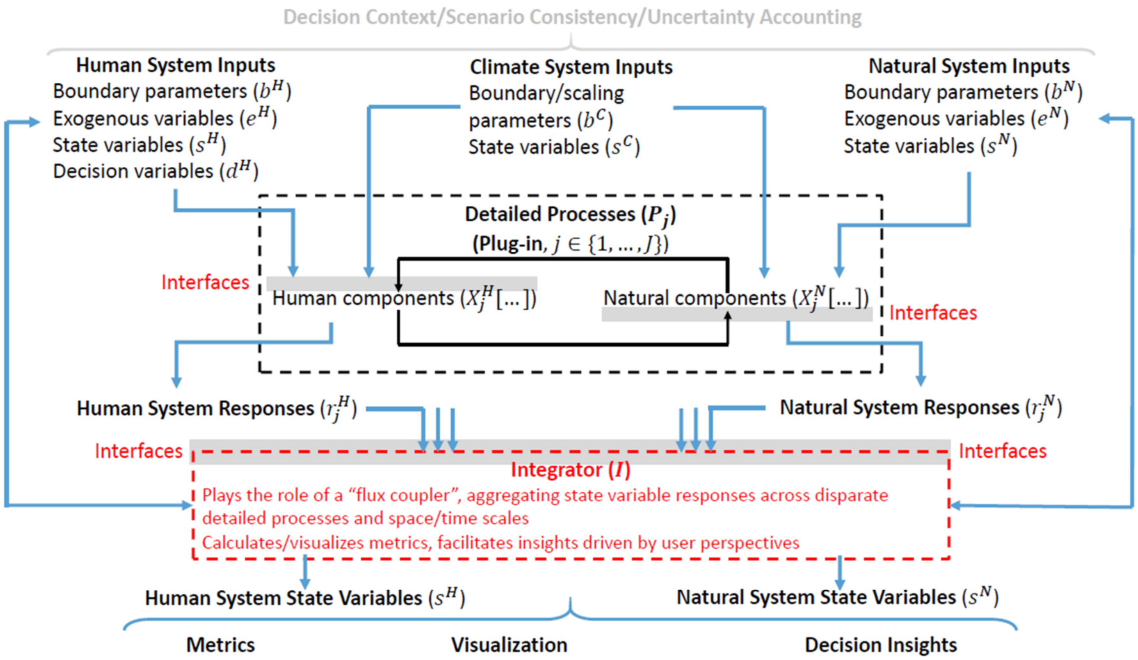


Figure IV-6. Conceptual structure proposed by one of the workshop breakout groups to integrate information on human systems, the climate system, and other natural systems across disparate processes and time/space scales.

In this abstraction, IAV modeling frameworks often encompass detailed process-based representations of interactions among a human system (identified by the superscript H) and/or a natural system (identified by the superscript N). These elements, indicated in the diagram by X^H and X^N, respectively, are themselves systems of mathematical relationships that could be individual models in their own right, or the sub-components of a larger, more complex simulation scheme. An "IAV model", shown by the dashed black rectangle at the diagram's center, can be conceptualized as a set of processes, indexed by j, that generally embodies interactions among human and natural components.

Each interacting component incorporates interfaces, upstream, to external sources of input data on which IAV models' constituent mathematical relationships depend, and, downstream, that provide information on system responses to climate change for external users of simulated results. Both streams of information are important because they define the vulnerability context of the analysis: attributes of the affected economic sector or natural system, as well as the status of physical impact endpoints and the effects of meteorological forcing on them. Inputs can be broadly classified into boundary parameters (b) that circumscribe the scope of inquiry, exogenous variables whose values are incorporated from other analyses (e), variables that track the states of system that the IAV model seeks to simulate (s), and, in the case of human components, decision variables (d). The variables b, e, and s archetypically represent attributes of the human system, non-climatic natural system, and the climate system itself—simulated by ESMs—

whose outputs are the principal driver of impact assessments. IAV models' outputs can be thought of as variables that track the response (r) of the simulated human or natural system to meteorological forcing.

A key feature of the figure is that the presence of interfaces emphasizes that IAV models generally do not just accept input data from the literature, or information that is passed to them, in some raw, native form. Similarly, the results of their internal computations are often not able to be directly accessed by downstream users. Rather, information inflow and outflow will almost always involve some kind of mathematical transformation (e.g., spatial and/or temporal aggregation or downscaling of climate model output), or, more subtly, conceptual translation (e.g., the transformation of gridded crop model yield responses into regionally aggregated impacts on the productivity land inputs to agriculture sectors within economic simulations—Nelson et al. 2014). An in-depth understanding of not only the interfaces themselves, but the assumptions and philosophies that underlie them, is a prerequisite to efforts to effectively link ESM, IAV, and IAM analyses.

Nowhere is this more important than in elucidating the potential feedbacks and synergies among the combined responses of human and natural systems to either multiple climate impacts, or a given impact across different economic sectors and/or geographic and temporal scales. It appears that the only way for such impacts to be consistently brought together is through the use of integrative models (I), shown by the dashed gray rectangle at the bottom of the diagram. One attractive feature of this broader modeling framework is that it can endogenously update the values of the state variables that are critical inputs to the human, and perhaps also natural, system components within IAV models, thereby facilitating an iterative multi-level process of assessment.

V. Implications for framework capabilities

The workshop was not intended to produce a detailed proposal for the framework, but discussion at the meeting and in subsequent meetings has advanced thinking about required capabilities and characteristics. Workshop outputs and additional information is incorporated in this section of the report on component models and data, needs for evaluation and uncertainty characterization, building capacity for decision support, and "nuts and bolts" issues such as the desirability of adopting a common set of naming conventions and development and use of a common software environment.

V.1 Models, data, and analysis methods

A major focus of the breakout groups was identifying and characterizing capabilities required for modeling each of the cases. Groups were asked to focus not just on models to represent key processes, drivers, and uncertainties, but also on data sets, decision-support tools, and other components that they would expect the framework to incorporate. The breakout groups were asked to identify the capabilities needed to address the problem they had defined, considering a specific configuration of data, models, and analytic tools that would produce metrics needed to answer a science question or provide relevant input to a typical decision maker confronted with the problem. Tables integrating all the capabilities were produced by many of the groups and addressed such issues as required spatial or temporal resolution, required data, type of model, example applications, and other aspects.

Approximately 100 distinct models, data sets, and other tools were identified by the breakout groups across the two workshop cross-cutting themes. No typology or taxonomy of capabilities was provided to the groups so that they could focus on identifying the unique capabilities required for each case. As a result, however, the groups often described similar capabilities differently, and/or identified capabilities that had some similarities but also notable differences. This variation made the process of aggregating information about the required capabilities and identifying common needs and gaps quite challenging.

After the workshop, members of the SSG developed a preliminary classification of capabilities. There was significant variation across the breakout groups, but some general needs were identified. We focus first on data, modeling, and analysis needs:

1. Climate/atmospheric systems: observational data and projections at a variety of scales from global to micro-level; statistical analysis of return periods for impacts-relevant variables; atmospheric chemistry/air-quality models (both outdoor and indoor);
2. Land systems: historical, current, and projected land cover and land use; digital elevation; data on zoning and other land-use restrictions;
3. Ecological systems/processes: dynamic vegetation models; projections of potential for pest outbreaks that would affect different systems; biogeochemical modeling; modeling of fire and other disturbance processes;
4. Coastal systems (sea-level rise/coastal flooding): projections of effects of global sea-level change at local scales; storm-surge modeling; coastal geomorphology and impacts of environmental and socioeconomic changes on erosion and sedimentation;
5. River systems and surface flooding: hydrological data and projections; surface-water hydrodynamics; subsurface infrastructure;
6. Energy/electric systems: historical and projected demand for different energy sources and carriers; supply scenarios (considering variation in fossil, nuclear, renewable sources); peak loads; high-resolution modeling of infrastructure systems; information on technology change to inform modeling of future infrastructure configurations;
7. Water systems: historical demand over time, considering different uses; water resources, considering quantity and quality of surface, subsurface, and additional (e.g., saline) sources; operation and planning of water-quality infrastructure (treatment plants, water utilities); modeling of reservoir and distribution systems including cost and performance; institutional/regulatory environment surrounding water supply;
8. Agriculture/bio-economy: food demand; bio-energy demand; historical data on bio-productivity (crops, forestry products, bio-energy, etc.); data on management and production practices; crop models for projections; scenarios of changes in agricultural technology;
9. Urban systems: demographic information; high-resolution GIS for different technology systems; movement of people, goods, and services; inflow/outflow of key commodities and products;
10. Transportation: transportation demand scenarios and modeling; high-resolution modeling of transportation infrastructure; historical data and projections of mode shifts; use of different fuels in meeting transportation demand under different scenarios;
11. Communications: high-resolution data on infrastructure; modeling of interdependencies with the other systems (e.g., energy, transportation, healthcare); location-specific analysis of technology use/types;
12. Healthcare systems: epidemiological modeling; high-resolution data on service infrastructure and capacity; modeling of healthcare demand;
13. Economic systems and processes: scenarios of development pathways; different types of economic models for projecting growth and transition; trade statistics and models; modeling of

interdependence of regional/local-level economies with demographic and other processes; income distribution;

14. Population and demography: historical and projected demographic characteristics at high spatial resolution; migration/displacement; spatially explicit population scenarios;
15. Institutional data and capacities: emergency preparedness; governance scenarios and constraints; policy/regulatory environment and priorities;
16. Resilience planning/decision support: visualization; decision analytic tools; communication and engagement methods.

Across the capabilities, groups noted the need for high-resolution models that incorporate detailed processes, as well as surrogate models that represent relationships of key variables over particular domains.

In the list above, we focus primarily on established domains of research and infrastructure/environmental/socioeconomic systems. In a sense, this captures the subject-matter content of individual needed capabilities, but not the challenges of establishing ways of connecting these capabilities, which we begin to address in the second list of bullets below.

Several groups noted that stakeholders may already have their own models that are relied upon and have credibility and legitimacy within a community of practice or within a regulatory body. This implies that it is desirable for the framework to have the capacity to take advantage of these existing models. But this does not suggest that new research should avoid developing models that duplicate existing capabilities, rather than that new models and analyses be evaluated and compared to an existing set of models and practices.

Looking across the large number of specific capabilities identified, a number of needs for development of new data, modeling, and analysis capabilities were discussed, including:

- Ways to represent extreme events at relevant spatial and temporal scales, including both high resolution and in reduced forms (e.g., through statistical analysis of return periods);
- More sophisticated fine-scale population/demographic distribution simulations/insights and coupling them with existing tools;
- Ability to model socio-economic shocks such as economic cycles, conflicts, mass migrations, epidemics, and other events that can also stress infrastructure, societal, and natural systems;
- Expansion of representations of human behavior, institutions, and social processes beyond economics to assess the potential to evaluate a broader set of questions with relevance to climate change impacts, vulnerability, and adaptation;
- Improved understanding of the ways in which different governance and institutional mechanisms affect function and resilience of infrastructure, natural, and socioeconomic systems, as well as advancing development of representations of institutional variables in models;
- Ability to represent individual networks and systems at high resolution and complexity, and to derive and represent aggregate statistics on network performance;
- Development of emulators of more complex representations of climate, environmental, infrastructure, and socioeconomic processes for coupling with other framework components;
- Creation of a carefully selected set of scenarios that bound possible future climate and socioeconomic regimes;

- Ways of measuring and communicating uncertainty and precision in variables (inputs and outputs).

This analysis is still a work in progress and will need further development as the framework is established. In particular, agencies and researchers will need to flesh out descriptions of available capabilities in terms of their technical characteristics that would enable other researchers to determine whether they would be useful in addressing problems or science questions they were attempting to model.

V.2 Evaluation, uncertainty characterization, and relation to decision-support capacities

Numerical models are imperfect representations of the real world processes they simulate, and uncertainty is associated with their results stemming from a variety of sources including inadequacy/lack of model completeness, lack of skill from calibration errors and other sources, poor input-data quality, and implementation problems. All of the component models discussed above are subject to these issues. For some, such as IAV and IA models, there are particular challenges to model evaluation. In some cases, the models were not necessarily developed with evaluation as a priority, and in others, suitable data are lacking for validation. On the other hand, some IAV and IA models are better suited to uncertainty characterization than Earth system models because they have shorter runtimes (and lower computational expense). Another factor that affects the extent to which component models have been evaluated is that on a scale from established modeling platforms to those that are more exploratory, many of the models being incorporated in this framework would still be considered exploratory, and thus there has been less opportunity for evaluation. The challenges of evaluation and analysis of uncertainty are compounded when applied to coupled models of complex systems because the uncertainties will propagate. In many cases, it is difficult to disentangle the contributions to uncertainty from different potential sources for a single component, let alone the integrated model.

For these reasons, research to develop the model framework must include careful attention to issues of validation and uncertainty characterization. Priority will need to be placed on development and analysis of input and model evaluation data, as well as on incorporation and adaptation of tools and software packages for exploring model design and uncertainty quantification. Specific approaches for evaluating and correcting errors will need to be developed and documented for modelers working within the framework. For some problems such as model incompleteness or lack of knowledge, process research to better understand how systems function will be required. For others, various analytic solutions and approaches for coordinating numerical experiments will be useful. Among the strategies mentioned in both topically focused and cross-cutting breakout groups were:

- Selecting cases of interacting impacts caused by past extremes for which data are available to evaluate both component models and coupled system response;
- Selecting cases for which different model representations are available for the same processes to compare relative performance;
- Designing the hierarchy of component models with flexibility and modularity to facilitate analysis of particular sub-components and dimensions;
- Use of sensitivity tests to reduce dimensionality and identify significant variables;
- Running coordinated scenarios and intercomparison projects;
- Extending probabilistic approaches for analysis of different drivers/influences;
- Development of emulators and "simple" models amenable to quantifying uncertainty across a range of parameter values;

- Development of a repository of emulators and simple models for cross-sectoral analysis and cross-model comparison;
- Development of visualization and other methods to facilitate analysis;
- Using decision analytic methods that identify the uncertainties with the greatest impact on the metrics of importance, thereby reducing the scope of uncertainty characterization.

One of the cross-cutting breakout groups specifically considered the issue of uncertainty and decision support, focusing on how progress can be accelerated by concentrating on the two challenges in an integrated way. Given the objective of using the framework to develop tools to assist decision makers, developing uncertainty characterization methods for metrics of importance to end-users would be a valuable strategy. Uncertainty will never be completely eliminated, and formal methods for decision making and design in the presence of uncertain inputs and model accuracy are needed to discover "no regrets" decisions that are both economically efficient and robust to uncertainties.

Decision support in this research endeavor involves bridging and integrating two very different groups of people and cultures: decision makers and scientists. Both are essential to the process. Those involved in decision making provide essential understanding of the decision context—the political, regulatory, economic, cultural, and other factors that influence a decision in addition to information from modeling. In addition, this set of stakeholders often includes managers and technical experts in infrastructure, environmental, and socioeconomic systems that are involved. Decision makers can identify critical variables, thresholds, and relevant metrics to sharpen the focus of the modeling and the uncertainty characterization better than a top-down approach could do. The research community provides its knowledge of how to represent the processes involved in the co-evolution of Earth systems, environmental conditions, and human processes. These two types of knowledge must be integrated in decision support.

An important point made in these discussions focused on the characteristics of information likely to be used by decision makers. For decision-support tools to be effective in linking scientific knowledge to action, the tools and resulting information need to be credible, salient, and legitimate. Credibility is frequently emphasized within the scientific community and refers to the validity, reliability, and technical accuracy of knowledge and analysis produced by a model. But the other characteristics are equally important from the perspectives of users. Salience is the degree of relevance of the information to the decision makers' needs, and legitimacy is the perception that the knowledge and information is produced in a way that respects norms such as transparency and access to underlying data and assumptions. Focusing on decision support adds issues to research on uncertainty that go beyond those associated with evaluating credibility of models. These issues include questions related to increasing salience and legitimacy. Some of the approaches mentioned for research in the framework included improving ways to develop scenarios with storylines (and associated quantification) that are meaningful to users, including at smaller spatial scales and more proximate time horizons. Another challenge identified is to develop methods for visualizing uncertainty to decision makers in a more intuitive fashion.

This analysis of effective decision support informed development of a schematic representation of a process and toolkit for modeling to improve understanding and inform decisions. The process begins with the decision makers' or scientists' questions and identifies the metrics required of the modeling and decision-support system. This helps ensure salience. Model forms are then developed to produce the identified metrics, considering model components coupled at appropriate levels of complexity. Model evaluation is a key activity, comparing the validity of results to historical data, but also considering the use to which the information is to be put. These components of the process contribute to credibility. In the kinds of problems being addressed in this framework, scenarios of the future are often used as a way of bounding irreducible uncertainty and establishing relevance to stakeholder issues. The final aspects of the process are related to tools for engaging stakeholders and communicating information, including steps such as evaluation of the decision-support process (See Figure V-1). These components of the process build legitimacy and salience.

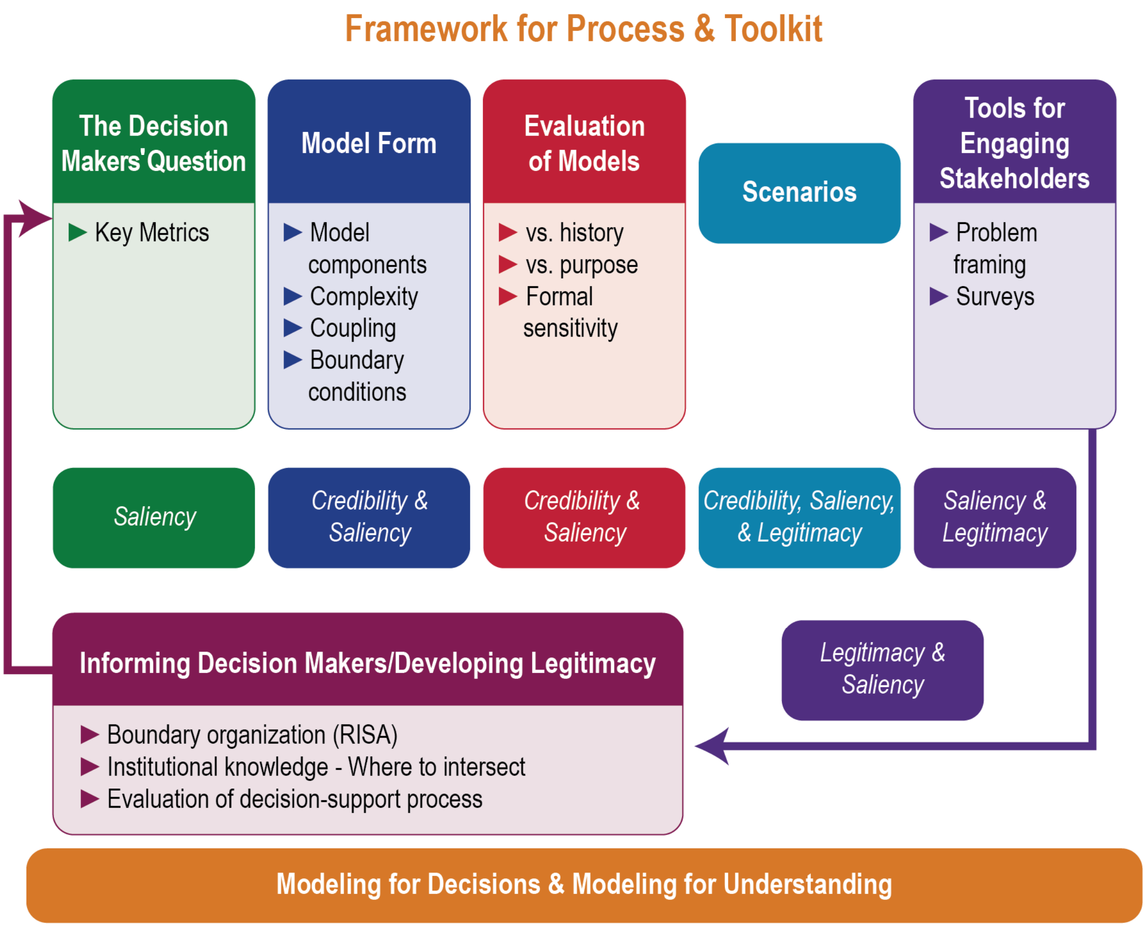


Figure V-1. Schematic representation of a process and toolkit for modeling to improve understanding and inform decisions. (RISA = Regional Integrated Sciences and Assessments) Source: Cross-cutting breakout group on "Model evaluation, uncertainty characterization, visualization, and decision support."

One of the approaches presented at the workshop used stakeholder engagement to identify information needs to reduce the number of models and processes represented, and to thus facilitate more careful analysis of the uncertainties most important for the question at hand (see Figure V-2). The process begins with stakeholder engagement to identify relevant metrics as well as characteristics of the decision-making environment that inform selection of communication methods. Only relevant models are coupled in a way that produces the identified information as efficiently as possible. Modeling teams participate in an elicitation process to identify potential sources of uncertainty, given the metrics being produced and the particular model configuration used. Sensitivity analysis is used to identify which uncertainties have the greatest effects, and for these variables, probability distributions will be developed and formal methods of uncertainty quantification applied. A variety of decision-support tools are used to communicate results with stakeholders. A conceptually analogous process applies to focusing uncertainty characterization for metrics used in hypothesis testing and answering science questions. Tools to prioritize and focus modeling and analysis would be useful as part of the overall capabilities of the framework.

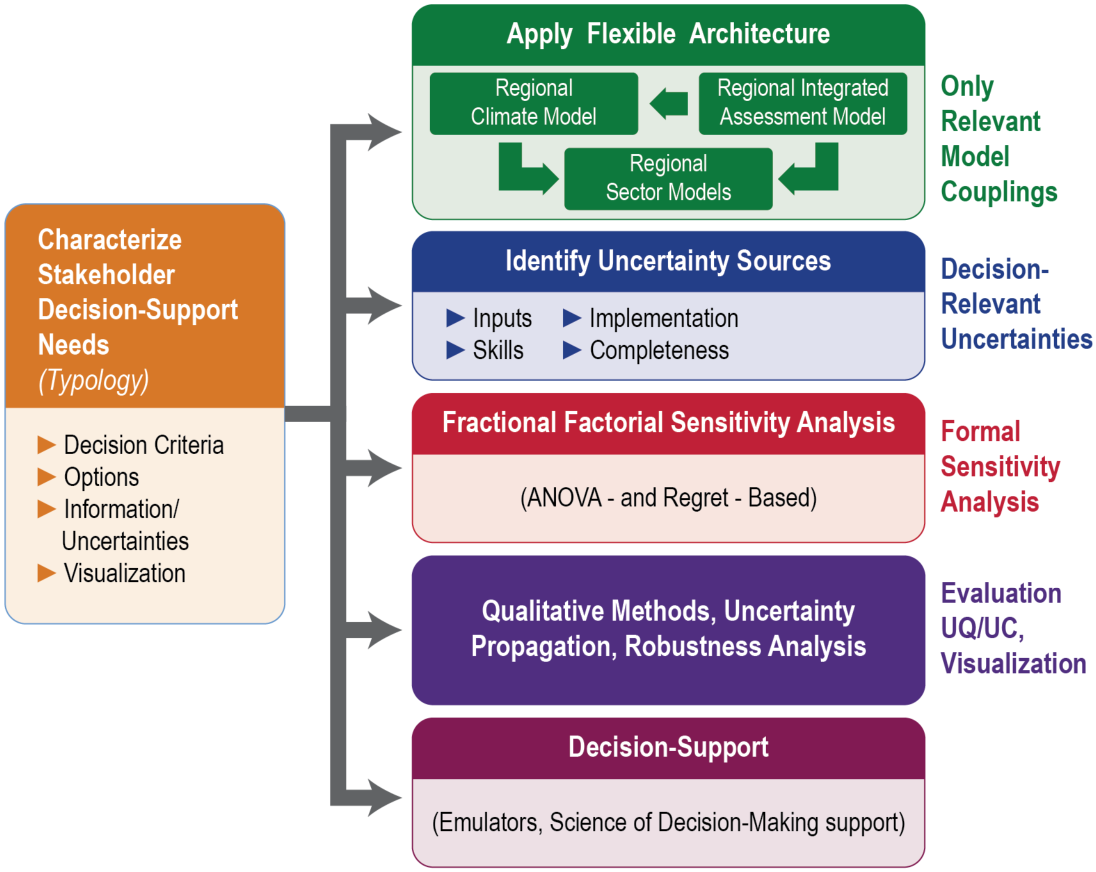


Figure V-2. Illustration of analytic process to reduce dimensionality of modeling and focus uncertainty characterization. Figures of merit drive selection and configuration of models as well as identification of key uncertainties that influence the results. Formal methods are then used to evaluate these key uncertainties and communicate results. (ANOVA = Analysis of Variance; UQ = uncertainty quantification; UC = uncertainty characterization) Source: Richard Moss

V.3 Enabling capabilities

Discussion of framework capabilities would not be complete without a brief mention of resources required to make it possible to couple different standalone models and data sets to work together. This topic was noted in several of the crosscutting breakout groups, and while it was not a major point of discussion in any of the plenary sessions, the SSG notes several key points in preparing this report.

Enabling capabilities are required to establish an environment that allows investigators to pursue their own research on these topics within a broader community of individuals working on similar science questions, and to build on the work of others by drawing on models, data, and methods they have developed. Because a model with fixed configuration would not effectively represent the many systems, processes, and feedbacks, many models, types of data, and analytic methods are required. These models can differ significantly. They include models of physical, engineered, ecological, and socioeconomic systems; they can use very different mathematical representations and approaches based on the different types of data they integrate or problems they are solving; programing language and software environments span a wide range; and they differ across other factors such as time step, spatial scale/resolution, gridding (if gridding is even used), and variable names/units (which can differ across models even for the same objects or processes). Thus mechanisms are needed to compare these different approaches and facilitate data and information interoperability between models. Examples of these services include shared semantic/naming conventions for variables and processes, converters of different sorts to translate data from one format to another, software environments for coupling, user interfaces, and other tools.

It is beyond the scope of this report to develop a complete list of the enabling capabilities required to facilitate interoperability, but given the discussion in breakout groups, the SSG does want to point out the importance of addressing these issues in a bottom-up fashion across different modeling teams who are beginning to work towards a shared multi-model framework. An early opportunity could be to start a process to develop a shared naming convention to ensure semantic consistency and avoid ambiguous variable names and attributes and establish common units for standardized variables. An integrated data-driven modeling, analysis, and visualization capability could be developed to understand, design, and develop to enable efficient access and usage of a set of common operating data, models, and tools shared across the community.

V.4 Data analytics, knowledge discovery, and advanced computational frameworks

Modeling requires a computational framework, and given the wide ranging and fragmented character of IAV, IA, and ES data and knowledge, the computational framework for this community of practice will need robust capabilities to generate, collect, synthesize, and analyze diverse cross-sectoral data at high spatial and temporal resolutions. This will enable, for example, understanding physical, engineered, and human system responses to changing climate and evolving critical infrastructures. An effective computational framework will be user driven and provide a broad suite of modeling, data, analytic, and visualization tools for research and operational communities addressing science questions and informing decisions at global to local scales, as well as across the public and private sectors.

Three major enabling capabilities are needed to facilitate the sort of collaborative, investigator-driven research envisioned:

- A robust data management and geo-visual analytics platform that provides access to disparate and distributed observational and simulation data for natural, engineered (including critical infrastructures), and socioeconomic systems;
- A collection of data conversion, integration, and mining algorithms, along with software and scalable computing resources to empower user-guided data inquiries, analysis and synthesis; and
- Resources for collaborative knowledge generation that facilitate leveraging and application of capabilities, state-of-the-art data integration, analysis and synthesis, and selected illustrative use cases for the implications of climate change for coupled systems.

Use of cyber-infrastructures for virtual integration across existing data portals will provide users access to authoritative and state-of-the-art data and information across the institutions producing and/or curating these products. This could also provide information and guidance for partners collaborating on development of shared resources and capabilities with regard to, for example, naming conventions.

Data analysis and visualization capabilities within such a framework need to be driven by science and use-inspired questions. The capabilities should be accessible and adaptable to the variety of different types of users, including researchers, analysts, city planners, and infrastructure engineers/designers. Visual feedback in the platform should be relevant, responsive, intuitive, and shareable. Adaptation solutions developed and deployed through the framework should meet specific needs and also be generalizable to other locations or systems.

Some of the core design principles of such a framework will include accessibility, interoperability, flexibility, integrity, reliability, security, and sustainability. These design principles will make it more likely that the framework provides essential enabling capabilities to the research community and other users. The capabilities of such a collaborative data and computational system are summarized in Figure V-3.

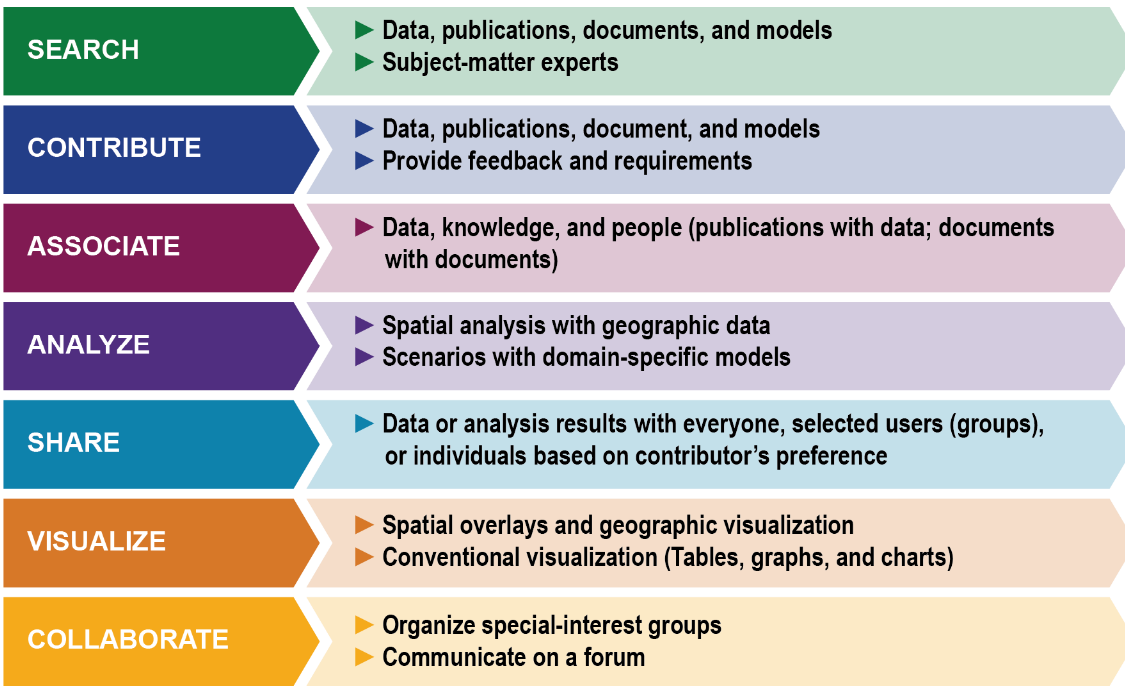


Figure V-3. Illustration of desirable capabilities of a collaborative knowledge, data, and computational system. Source: Budhendra L. Bhaduri, ORNL.

VI. Beyond the workshop: opportunities and challenges

VI.1 Developing a community of practice

At the workshop, participants explored what they considered to be a set of "grand challenges" in two senses: first, in terms of the problems confronting society, and second in terms of needed advances in science. But developing a framework such as the one envisioned here is a grand challenge in another sense as well: bringing the different research and user communities together, developing the environment, and having participants use the resulting tools to facilitate meaningful collaborations. This is a grand challenge on many levels including identifying the problems that need to be addressed, getting the right vocabulary, and breaking down barriers between disciplines. If this effort is to succeed, it needs to develop a way to sustain interactions. It needs to establish a new paradigm, not just in terms of a model, but by developing and sustaining a community of practice.

Although daunting, this is not a unique challenge. Groups have addressed similar interdisciplinary problems using a community of practice approach before, and their solutions can help guide these efforts. One example within the climate science community is the Community Earth System Model (CESM), which builds upon contributions from often independently developed ocean, atmosphere, sea-ice, land, agriculture, ecosystems, air-chemistry, and stratosphere dynamics modeling efforts. Another is the Community Surface Dynamics Modeling System (CSDMS), which adopts a similar approach to making it possible to integrate land surface, terrestrial ecosystem, hydrologic, coastal, biogeochemical, climate, and other models to explore fluxes of energy, water, nutrients, and other processes needed to understand global change. In these examples, multiple disciplines and research traditions are involved, each with its own set of theories, methods, and language. The frameworks these communities use help participating scientists expand the perspectives and tools at their command. They provide approaches for coupling models and data in standardized methods and tools available to anyone in the group. There are lessons from these and other examples in how to develop modeling frameworks—these indicate a lot of coordination, effort, time, and resources are required to make this happen.

Three features that may be unique in the cases discussed at the workshop include (1) the degree of complexity in interactions across systems involving Earth natural resources, infrastructure, socioeconomic, and Earth system processes; (2) the diversity of disciplines and tools involved; and (3) the emphasis here on use-inspired or problem-driven science. These characteristics may add to the degree of challenge that this community will face in building a framework of tools and capabilities.

To establish a community of practice to promote research on these complex co-evolving systems, participants will need to work on establishing a culture and language across different disciplines. They will need to think about incentives and whether the benefits and added complexity are worth the effort. And they will need to think beyond the practical problems represented in the cases because this effort is unfolding under the auspices of research programs that need to maintain a focus driven by science questions. The challenge is not primarily about the subsystems (building better component models and data sets), but rather developing a focus on integration. Community involvement needs to be built around the objective or promoting accessibility. It should not demand tremendous amounts of time or be resource intensive. It should provide "off-ramps" for connecting science to use-inspired tools. A focus on community building includes identifying the principles by which these different disciplines might define common problems or objectives. If the process becomes too prescriptive, it will discourage participation. The scientific curiosity of the research communities, in interaction with awareness of the information needed by users, should be allowed to drive the process.

Participants discussed some good practices that could be used to guide the process of establishing a framework, including:

- Adopt a clear focus on problem(s) of interest;
- Identify what data/information is needed to make better decisions;
- Draw upon a range of capabilities and knowledge including models, observations, and expert opinion;
- Ensure provenance capture, repeatability of results, and transparency of metadata;
- Clearly define inputs and outputs (i.e., metrics) to be shared;
- Understand data traditions/needs (social science surveys, physical observations, etc.), including geographic and temporal aggregation/disaggregation.

VI.2 Options for moving forward: multiple approaches for community building

The workshop participants considered options for advancing the framework and community of practice. To start with, participants felt that the cases identified by the agencies and discussed in the breakout groups provided an appropriate and emblematic set of challenges to focus on. Building on these cases, some modest next steps that were identified included:

- Using the data generated in the workshop as a start, identify the set of system elements common to multiple use cases. Inventory/screen/evaluate the set of existing modeling elements with the capabilities to simulate the detailed natural- and social-science processes at the core of these system elements.
- For each of the tools identified in the workshop, scope their attributes and identify information flows. This identifies and motivates the needs for interfaces, and combined with the decision/problem context, clarifies what models need to be integrated in what ways.
- Establish metadata standards to define what "plug in" actually means, facilitating decisions about what will be integrated with what else, in what order, and why.
- Start with basic sensitivity testing and scenario analysis to establish what is important in coupling process representations, for what questions(s) and user(s). The complexity of this challenge needs to be recognized, with initial steps taking on relatively simple cases.

Looking back at suggestions made during the workshop and subsequent meetings, a number of "tried and true" approaches for facilitating this research were identified. These included workshops, coordinated experiments, intercomparison activities, a wiki or other method for sharing information about capabilities as they are developed, targeted research competitions, and similar activities. Participants offered a number of ways of innovating some of the approaches to make them better tailored to the need for sustained interactions among the different research communities so that mutual comprehension of the challenges and approaches that the different communities bring to the effort can be achieved.

A number of participants suggested it was important to establish opportunities for diverse groups of researchers to work together on specific cases in project teams. One idea that is new to the community of IA and IAV researchers is to establish regional test beds for data, modeling, and analysis. These test beds could be coordinated around priority problems in different regions and would be used to develop and evaluate combinations of data and models needed to address the problems. In addition, they would provide opportunities to integrate users into a co-production process to develop approaches for making the scientific results accessible and usable in evaluating choices confronting decision makers. The test beds would provide practical examples of the utility of the integration of observational data, modeling, analytic, and decision-support tools spanning scales and systems. They would be expected to draw upon advanced computing and analysis methods.

One obvious focus for such an activity is created by the urgency to address challenges at the energy-water-land interface in better integrated ways. This need is driven by changes in extreme weather patterns, resulting floods and other disasters, accelerated drawdown of critical water supplies, and socioeconomic trends that result in location of infrastructure and populations in vulnerable locations. Regional test beds focused on such topics could address science challenges and information needs articulated by the agencies that sponsored and participated in the workshop. But rather than approaching these topics from the perspectives of individual systems, sectors, or users, projects would be solicited from research and user communities that integrated multiple-use perspectives into a single project, thus requiring research into how different infrastructure systems co-evolve under environmental, socioeconomic, and Earth-system processes. To ensure that the test beds evaluated issues beyond technical performance of the data, modeling, and analysis systems, engagement could be encouraged from multiple decision-making bodies and institutions that do not interact or typically do not share information in order to evaluate the ability of the framework to produce useful insights about feedbacks and interactions that could lead to improved investment and adaptive management decisions.

Addressing these issues would require the test bed teams to improve individual model capabilities as well as to explore approaches for providing some of the enabling components and tools discussed above. As test beds, significant emphasis would be placed on model evaluation. There are numerous opportunities to integrate new data sources, use large data sets relevant to understanding changing resource use and demand patterns, integrate observational data, and collect/create new data sets required to integrated relevant information across scales and domains for both environmental and socioeconomic processes. Extreme-scale computational facilities would enable complex modeling, processing, and data analytic approaches that will make it possible to understand how feedbacks and dynamics across systems could affect resilience of critical infrastructure and environmental systems. Earth systems science would require high-resolution representations of atmospheric, oceanic, and terrestrial processes across multiple scales. Development of formal decision-analysis methods could also be encouraged to create methods to identify promising options for increasing system resilience and discovering "no regrets" options that are economically efficient, environmentally sustainable, and robust to uncertainties. These would also place high demands on computational and data resources.

Appendix A – Workshop Program

(See next page for Workshop Program.)

IA-IAV-ESM WORKSHOP

TOWARD MULTI-MODEL FRAMEWORKS ADDRESSING MULTI-SECTOR DYNAMICS, RISKS, AND RESILIENCY

A Workshop of the U.S. Global Change Research Program's
Interagency Group on Integrative Modeling
and Interagency Coordinating Group

May 24-26, 2016

PNNL Joint Global Change Research Institute, College Park, MD

U.S. Global Change
Research Program

INTERAGENCY COORDINATING GROUP

Robert Vallario, U.S. Department of Energy (ICG Chair)
Gerald Geernaert, U.S. Department of Energy (USGCRP Vice-Chair)
Gregory Anderson, National Science Foundation
Jeffrey Arnold, U.S. Army Corps of Engineers
John Balbus, National Institutes of Health
Hoyt Battey, U.S. Department of Energy
Diana Bauer, U.S. Department of Energy
Jessie Carman, National Oceanic and Atmospheric Administration
Paul Cohen, Defense Advanced Research Projects Agency
Charles Covel, U.S. Department of Homeland Security
Benjamin DeAngelo, U.S. Global Change Research Program
Anne Grambsch, U.S. Environmental Protection Agency
Fiona Horsfall, National Oceanic and Atmospheric Administration
Margaret Lange, National Geospatial-Intelligence Agency
Michael Lenihan, National Geospatial-Intelligence Agency
Jia Li, U.S. Environmental Protection Agency
James McFarland, U.S. Environmental Protection Agency
Robert O'Connor, National Science Foundation
Marilee Orr, U.S. Department of Homeland Security
Alexander Ruane, National Aeronautics and Space Administration
Ronald Sands, U.S. Department of Agriculture
ICG Coordinator: Alison Delgado, U.S. Global Change Research Program/JGCRI-PNNL

SCIENTIFIC STEERING GROUP

Scott Backhaus, Los Alamos National Laboratory
Christopher Barrett, Virginia Tech
Budhendra Bhaduri, Oak Ridge National Laboratory
Karen Fisher-Vanden, Pennsylvania State University (Co-Chair)
Ian Kraucunas, Pacific Northwest National Laboratory
Richard Moss, Joint Global Change Research Institute, PNNL (Co-Chair)
Patrick Reed, Cornell University
Jennie Rice, Smarter Decisions, LLC
Ian Sue Wing, Boston University
Claudia Tebaldi, National Center for Atmospheric Research

INTERAGENCY GROUP ON INTEGRATIVE MODELING

USGCRP's Interagency Group on Integrative Modeling (IGIM) coordinates global change-related modeling activities across the Federal Government and provides guidance to USGCRP on modeling priorities. The 10 Federal agencies that participate in the IGIM engage on a range of relevant topics, including physical models of the Earth system, socioeconomic models of human systems and their interactions with the Earth system, and impacts models.

Photo Credits: Selected photos from the Third U.S. National Climate Assessment, 2014 (http://nca2014.globalchange.gov); U.S. Department of Energy, 2014: *The Water-Energy Nexus: Challenges and Opportunities*; U.S. Environmental Protection Agency, 2010 (https://www.epa.gov/chesapeake-bay-tmdl); and U.S. Global Change Research Program, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (http://dx.doi.org/10.7930/J0R49NQX).

DAY 1 | May 24

8:00 AM - 9:00 AM
Registration and Breakfast
(Room 4058 ESSIC Lounge)

I. INTRODUCTION AND OVERVIEW OF FRAMEWORK CONCEPT

(Plenary, Room 4102)

9:00 AM: Workshop Welcome
Gerald Geernaert

9:05 AM: Welcome to the Institute
Ghassem Asrar

9:10 AM: Agenda Overview
Karen Fisher-Vanden / Richard Moss / Alison Delgado

II. MODEL FRAMEWORK CONCEPT: USER TYPOLOGIES, MODELING DOMAINS, & LEVELS OF COMPLEXITY

(Plenary, Room 4102)

9:15 AM: IAV-IA-ESM Multi-Model Framework – Needs, Opportunities, and Context
Robert Vallario

9:25 AM: User Typology to Inform Framework Development
Richard Moss

9:35 AM: Overview of Classes of Models and Resources and Framework Concept
Karen Fisher-Vanden

9:50 AM: Plenary Discussion
Clarifying objectives, opportunities, and challenges of a framework for research and modeling of coupled human-environment systems in a multi-stressor world

EXAMPLE MODELS AND CAPABILITIES

Chair: Jim McFarland
(Plenary, Room 4102)

10:00 AM: Ian Kraucunas on multi-scale modeling

10:10 AM: Christopher Barrett on micro-simulation applications in human health

10:20 AM: Scott Backhaus on connected integrated infrastructure modeling

10:30 AM: Discussion

11:00 AM: Coffee Break

III. CONCENTRATED AND CONNECTED INFRASTRUCTURE

(Plenary, Room 4102)

11:30 AM: Panel: Interagency Coordinating Group (ICG) Members Introduce Example Uses
(10 minutes each)
Chair: Diana Bauer
(Example use topics are listed on page 3)

12:10 PM: Discussion

12:30 PM: Lunch
(Room 4058 ESSIC Lounge)
Breakout group co-chairs meeting in Room 3502 (30 minutes)

1:30 PM: Breakout Group Instructions
(Plenary, Room 4102)

1:45 PM: Breakout Groups
(Room numbers found in table on page 3)

DAY 1 WRAP-UP

(Plenary, Room 4102)

5:00 PM: Comments from Organizers and Participants; Review Overnight Assignment: Table of Capabilities and Models

5:30 PM: Adjourn

DAY 2 | May 25

8:30 AM - 9:00 AM
Registration and breakfast
(Room 4058 ESSIC Lounge)

PANEL DISCUSSION: INFRASTRUCTURE BREAKOUT GROUP RESULTS

Chair: Robert O'Connor
(Plenary, Room 4102)

9:00 AM: Reports from Breakout Groups: Implications for Model Framework

10:00 AM: General Discussion

10:15 AM: Coffee Break

IV. DROUGHT AND INCREASED VARIABILITY OF WATER SUPPLY

(Plenary, Room 4102)

10:45 AM: Panel: ICG Members Introduce Example Uses (10 minutes each)
Chair: Jessie Carman
(Example use topics are listed on next page)

11:25 AM: Discussion

11:45 AM: Lunch
(Room 4058 ESSIC Lounge)
Breakout group co-chairs meeting in Room 3502 (30 minutes)

1:00 PM: Breakout Group Instructions Revisited (as required)
(Plenary, Room 4102)

1:15 PM: Breakout Groups
(see room numbers in the table on the next page)

DAY 2 WRAP-UP

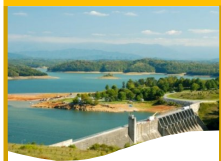
(Plenary, Room 4102)

4:30 PM: Comments from Organizers and Participants; Review Overnight Assignment: Table of Capabilities and Models

5:00 PM: Adjourn

5:00-5:30 PM: Meeting of Breakout Group Chairs, Rapporteurs, and ICG/SSG Members
(Room 3502, JGCRI Third Floor)

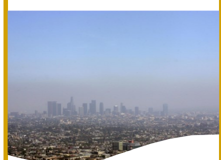
Agency Example Uses: Concentrated and Connected Infrastructure



1.1 Electric system reliability and demands affected by water quantity/quality |
Room 4102, Plenary
ICG co-chair: Robert Vallario, U.S. Department of Energy
SSG co-chair: Scott Backhaus, Los Alamos National Laboratory

1.2 Health services affected by cascading infrastructure failures and interdependencies |
Room 4056, Small Conference Room
ICG co-chair: John Balbus, National Institutes of Health
SSG co-chair: Christopher Barrett, Virginia Tech

1.3 Coastal city inundation affected by sea level rise and extreme weather events |
Room 4046, "Classroom"
ICG co-chair: Charles Covel, U.S. Department of Homeland Security
SSG co-chair: Ali Abbas, University of Southern California



1.4 Urban socioeconomic systems and vulnerable communities affected by heat waves and air-quality events | Room 3502, JGCRI Third Floor
ICG co-chair: Jia Li, U.S. Environmental Protection Agency
SSG co-chair: Jennie Rice, Smarter Decisions, LLC

Agency Example Uses: Drought and Increased Variability of Water Supply

2.1 Reservoir resilience affected by droughts, floods, and changing extremes |
Room 4102, Plenary
ICG co-chair: Kate White, U.S. Army Corps of Engineers
SSG co-chair: Patrick Reed, Cornell University

2.2 State economies, including agriculture, affected by drought |
Room 4056, Small Conference Room
ICG co-chair: Ronald Sands, U.S. Department of Agriculture, and Alexander Ruane, National Aeronautics and Space Administration
SSG co-chair: Karen Fisher-Vanden, Pennsylvania State University

2.3 Planning for wildfire impacts and management under changing climate, environmental, demographic, and policy futures | Room 4046, "Classroom"
ICG co-chair: Linda Langner, U.S. Department of Agriculture Forest Service
SSG co-chair: Claudia Tebaldi, National Center for Atmospheric Research

2.4 Surface-water quality and ecosystem services affected by droughts, floods, and changing land use/land cover trends | Room 3502, JGCRI Third Floor
ICG co-chair: Anne Grambsch, U.S. Environmental Protection Agency
SSG co-chair: Ian Kraucunas, Pacific Northwest National Laboratory

DAY 3 | May 26

8:30 AM - 9:00 AM

Registration and breakfast
(Room 4058 ESSIC Lounge)

PANEL DISCUSSION OF DROUGHT BREAKOUT GROUP RESULTS

Chair: Benjamin DeAngelo
(Plenary, Room 4102)

9:00 AM: Reports from Breakout Groups: Implications for Model Framework

10:00 AM: General Discussion

V. CROSS-CUTTING ISSUES

10:15 AM: Cross-cutting Breakout Group Instructions
(Plenary, Room 4102)

10:30 AM: Coffee Break

11:00 AM: Breakout Groups on Cross-Cutting Issues (see room numbers in table on next page)

12:30 PM: Lunch

(Room 4058 ESSIC Lounge)

1:30 PM: Cross-Cutting Group Reports

Chair: Jia Li
(Plenary, Room 4102)

Report back from cross-cutting breakout sessions (10 minutes each) followed by discussion

VI. FINAL PLENARY: THE WAY FORWARD

Chair: Charles Covel
(Room 4102)

2:30 PM: Closing Panel Discussion: Final Synthesis and Next Steps

Robert Vallario, Marilee Orr, and Alexander Ruane

3:00 PM: General Discussion

3:30 PM: Close

Gerald Geernaert

Cross-Cutting Topics

Group 1 – Framework Vision (Co-Chairs: Anne Grambsch and Ian Sue Wing) | Room 4102, Plenary

Looking across the opportunities and needs identified by the different breakout groups, develop ideas for the framework's overall vision, near term wins/advances, and long-term research needs. Consider the question, "if we have this framework, what would we do with it?" What science questions and scenarios could be investigated? What are some of the priority application areas that could benefit from a framework such as this?

Group 2 – Tools for modeling across multiple scales and sectors (Co-Chairs: Marilee Orr and John Weyant) | Room 4056, Small Conference Room

Given the capabilities identified by different breakout groups, what are some of the key model development needs that must be addressed to make progress in developing the framework, e.g., coupling strategies, model hierarchies, software development, need for emulators, increased cross-scale and interdisciplinary coordination of scenarios, etc. What strategies would be effective in developing and implementing the framework (e.g., a framework wiki, periodic conferences, targeted competitions to develop components, software specifications)?

Group 3 – Data: What other information do we need to gather? (Co-Chairs: Jay Hnilo and Deborah Balk) | Room 4046, "Classroom"

What are some of the major opportunities and gaps with respect to data for different dimensions of the framework and different spatial/temporal scales of analysis? Is there a typology that can be used to describe data needs? What emerging approaches could we harness, for example opportunities for machine learning and data analytics?

Group 4 – Model evaluation, uncertainty characterization, visualization, and decision support (Co-Chairs: Jim McFarland and Rob Lempert) | Room 3502, JGCRI Third Floor

Considering the use perspectives addressed in the breakout groups, what are some of the common elements/needs related to uncertainty characterization, visualization, interfaces, scenarios, etc.? What are some of the grand challenges, for example extending probabilistic approaches for analysis of different drivers/influences, including climate change? What approaches and priorities should be established for model evaluation?

WORKSHOP BACKGROUND & OBJECTIVES

This workshop is one of several efforts convened under the auspices of the U.S. Global Change Research Program that are intended to develop concepts for a modeling framework or architecture to couple Impacts, Adaptation and Vulnerability (IAV) models; Integrated Assessment (IA) models; and climate, Earth system, hydrology, land use, demography, and other models. The framework will facilitate integration of a wide range of model capabilities to meet a growing societal need to better understand the potential for cascading impacts of interacting societal and environmental change across sectors and scales. The workshop is being coordinated by an Interagency Coordinating Group with technical inputs from a Scientific Steering Group. The agencies that comprise the workshop's Interagency Coordinating Group share a common interest in the scientific challenges associated with modeling the interactions of human and environmental systems to support risk management.

The workshop addresses the following challenges:

Systematize needs and uses: Explore uses, scale and information dependencies associated with these uses, and specific information needs for categories of problems. Discussions at the workshop are intended to help development of a "use typology" that will identify needs to guide research and development of the framework.

Inventory and evaluate the state of science: Inventory extant and emerging models and frameworks for representing and integrating key processes and interactions. This will include evaluating sector-specific IAV models (ranging from those focused on resource productivity to market interactions), IAMs, a range of approaches for characterizing changes in climate and related physical systems (e.g., hydrology, land cover), and methods for modeling socioeconomic systems and behavior. The workshop will explore data requirements, coupling strategies, mechanisms to capture impact and adaptation information that is not amenable to modeling, approaches for evaluating risk, and model evaluation.

Develop the conceptual framework: Discuss a conceptual framework for research and modeling that defines data and coupling needs by identifying interactions across scales, sectors, and temporal processes essential for addressing the problems and information needs. Participants will also explore the near-term mechanisms and activities for implementation of the framework concept in ongoing and planned model development activities across the USGCRP and interested research community.

Identify research needs/opportunities and options for program development: Explore needed advances in fundamental research on Earth systems, environmental, and societal processes; specialized sector-specific models; and models able to represent interactions and tradeoffs across sectors, systems, and time/spatial scales that can contribute to advancing the state of science. This will include identifying research gaps and priorities for different intended applications and user communities.

Interagency workshop sponsored by the U.S. Department of Energy on behalf of the U.S. Global Change Research Program

U.S. DEPARTMENT OF ENERGY | Office of Science

Appendix B – Presentations & Breakout Group Discussion Summaries

Contents

This appendix provides summaries of the presentations on advanced modeling approaches, including integrative frameworks, modeling of infrastructure networks, and micro-scale, agent-based modeling of micro-scale individual behavior and institutional response. The second part of this appendix provides descriptions of the user-focused integrative themes on *Concentrated and Connected Infrastructure* and *Drought and Increased Variability of Water Supply*. It summarizes the major points discussed in each breakout group and related follow-up discussions during the plenary report-outs. Prior to the workshop, the co-chairs for each breakout group prepared a description of a user-focused example where an integrated modeling framework is needed. These write-ups, in addition to a set of questions prepared by the ICG and SSG (see Appendix C), were used as background material and basis for the breakout group discussions at the workshop.

B.1 Example Capabilities and Frameworks

Several presentations on the opening morning of the workshop provided examples of cutting-edge modeling and analytic capabilities and integrated modeling frameworks that illustrated some of the challenges and methods needed to develop the framework. The first section of this appendix briefly describes these presentations.

B.1.1 Micro-to-Macro Population Informatics: The End of Monolithic Models for Human-Coupled Decision Analytics, Christopher Barrett (Virginia Tech)

The first presentation focused on the use of high-performance computing, network science, behavioral modeling, and other analytic techniques to address complex sociotechnical challenges such as health risks. Barrett highlighted an integrated modeling framework for investigating the complex dynamics of socially coupled systems such as transportation, built infrastructure, and health, drawing on disciplines including computer science, urban planning, economics, and statistics. The core approach is based on using synthetic (anonymized) fine-grained representations of populations together with large-scale, agent-based simulations and analyses. A specific application for this framework is in the study of the coevolution of networks (consisting of both human and technical elements), individual behaviors, and epidemics. The model can provide decision makers with information about the consequences of an outbreak, the resulting demand for health services, and the feasibility and effectiveness of various adaptations. An attractive feature of this framework is that human interactions and decision processes are represented in the model.

B.1.2 On multi-scale, multi-sector modeling of climate impacts, responses, and feedbacks, Ian Kraucunas (Pacific Northwest National Laboratory)

The second presentation provided insights from two regional integrated modeling frameworks: the Platform for Regional Integrated Modeling and Analysis (PRIMA), and the subsequent DOE Regional Integrated Assessment Modeling (RIAM) project. Both PRIMA and RIAM link a variety of component models to simulate the complex interactions among climate, energy, water, land, and related systems at decision-relevant spatial scales. The framework's component models include a regional ESM, an IAM with enhanced domestic resolution, and a number of individual sector models. Both of these projects have helped to improve our understanding of the benefits and challenges associated with integrated, multiscale modeling. Kraucunas highlighted the importance of using a flexible coupling approach (depending on the application, only some of the component models will be needed, and only some of their outputs will be relevant to the problem being addressed); ensuring consistent boundary conditions; creating a platform that is portable and modular so that different regions can be more easily analyzed and any component can be replaced by a different representation of the same system; and having both the framework and its outputs be open source to enable its use by both researchers and decision makers. A common challenge has been in developing data transformations needed to bridge temporal scales and spatial scales, as well as integrating geospatially resolved component models with those that are not.

B.1.3 Interdependent Infrastructure Network Models: Thoughts for the Breakout Sessions, Scott Backhaus (Los Alamos National Laboratory)

The last presentation under this session touched on the trade-offs between highly detailed infrastructure network models and more simplified ones. Individual infrastructure networks (e.g., electric power or natural gas networks) may already be too complicated to optimize or simulate using “full physics” or at “full spatiotemporal” resolution. Reductions, simplifications, approximations, or relaxations are often needed. However, these modifications affect the fidelity of the results, and they impact how, or even if, networks can be coupled in a principled manner. Backhaus illustrated this with an example of a natural gas system. In order to evaluate the capacity of a pipeline to deliver gas to customers over the course of a day, one might be tempted to use temporal averaging to get from a dynamic to a static model. This would not take proper account of temporal and spatial variability and correlations in the gas flows on the system, resulting in loss of model fidelity. These issues could be addressed with more complex models or better averaging techniques. Also, how individual networks are represented determines how models can be coupled. It is very difficult to couple an averaged, highly aggregated network with a system that contains many network details. With these modeling constraints in mind, Backhaus proposed considering the following questions when modeling connected infrastructure: What is the spatiotemporal scale of your infrastructure questions, and what is the appropriate meshing of the spatial and temporal scales between the different network systems? Second, if a simplified model of an infrastructure is preferred, what are you losing? Is the loss of fidelity too severe for the questions you are trying to answer? Finally, are you analyzing the system or are you providing decision support? If the latter, how are you providing that decision support? Are simulations of numerous scenarios sufficient to provide decision support, or should you move to a different optimization formulation when moving into decision-support activities?

B.2 Integrated Themes on Concentrated and Connected Infrastructure

B.2.1 Electric system reliability and demands affected by water quantity/quality, Co-leads: R. Vallario (DOE) and S. Backhaus (LANL)

Problem framing

Electrical power production represents one of the largest uses of water in the United States and worldwide. As water demand from the power sector combines with pressures from population growth and other competing water uses, there are increasing concerns over water availability and water quality, particularly during droughts and heat waves; in some parts of the United States, these episodic events are expected to become more frequent over the next century. Although agriculture dominates the consumption of water, thermoelectric cooling dominates the withdrawals of water, accounting for 45 percent of total water withdrawals in the country in 2010 (the largest water use that year).[3] Thermoelectric cooling is required across many fuels and energy sources, including nuclear, natural gas, coal, concentrated solar power, and geothermal.

[3] Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). Estimated use of water in the United States in 2010 (No. 1405). U.S. Geological Survey.

The water and energy sectors also have important connections to land, climate (both global and regional), technology options and strategies, and broader aspects of socioeconomic development, such as population, migration, regional economics, and local, regional, and national institutional factors.[4] These variables necessarily span several temporal and spatial scales.

Recognizing the need for improved, integrated, regional/local planning and risk assessment for electricity supply and transmission in the context of changing stream flows and water temperature, this breakout group addressed the following questions:

> *What are the stressors and integrated infrastructural risks arising from evolving vulnerabilities to water-cooled thermoelectric generation? What adaptation measures (operational rules, design, siting, importation, technology, institutional/regulatory, etc.) in the supply and transmission of electric power are most likely and viable for different regions to mitigate these vulnerabilities?*

The desired modeling framework/architecture would help to assess key metrics such as duration and extent of unplanned outages and/or poor power quality; mean down-time of vital infrastructural services due to electricity disruptions; congestion in the electric grid, levelized cost of electricity; impacts of reliability on regional economic development (business and industry); and mortality/morbidity due to loss of electricity services. The group also expressed interest in the evaluation of scenarios of gradual as well as rapid disruptive changes (systems "shocks") that cause both chronic and episodic system stress.

User perspective and needs

The breakout group approached the questions from the perspective of a regional electrical transmission system operator or state public utility commissioner whose systems cut across several geospatial boundaries (e.g., spanning several states, or having an urban-to-rural transect encompassing several counties). Regional operators and utility commissioners are responsible for ensuring that their regions have reliable and sustainable infrastructural services. They are interested in capabilities that could help improve Integrated Resources Planning and identify significant dependencies spanning sectors and uncontrollable factors; assess sources of demand for water and changing supply of water; assess water-environmental concerns; and gain a better understanding of market uncertainties and marginal costs/cost structures, laws, and regulatory issues for both water and energy, and capacity requirements for dispatchable capacity. Some of the questions that system operators and state public utilities may be interested in exploring are:

- What are the risks and potential evolutionary pathways that mitigate both chronic and episodic infrastructure stress?
- What are the potential unintended consequences of adaptation?
- What can we learn from "stress-testing" the system?
- What are the implications for changes to the electricity system in the pursuit of integrated risk management spanning connected infrastructures and services tied to reliable electricity service?

The breakout group agreed that the following user-driven desired outcomes are important, and provide nuanced perspectives to the problem:

- Near-term and long-term integrated/holistic resource planning under high uncertainty;

[4] U.S. Department of Energy (2014). The Water-Energy Nexus: Challenges and Opportunities.

- Meeting demand at minimum cost and acceptable reliability;
- Improving resilience (resilience is not currently tracked and there is need for such metrics);
- Long-term view on stranded assets;
- Regulatory compliance.

Drivers

A myriad of systems, processes, and interactions affect thermoelectric generation. The breakout group noted the following as drivers or other interacting processes that should be acknowledged in this modeling framework:

- Precipitation, stream flow, stream temperature;
- Extreme weather events (droughts/floods);
- Diversification (or concentration, e.g., towards natural gas?) of generation portfolio;
- Projection of demand and demand growth;
- Electric and water infrastructure growth and expansion;
- Technology availability and cost;
- Changing water and energy demands brought about through population/migration changes, increased consumptive water use (e.g., agricultural withdrawals or diversions) or increased electricity demand (e.g., higher agriculture water pumping and air conditioning during heat waves);
- Groundwater and groundwater depletion;
- Reservoir management;
- Water-quality changes;
- Institutional/policy/regulatory;
- Redundancies, backups, and safety margins built into broader infrastructural dependencies.

The breakout group also thought about major sources of uncertainty in models that address the energy sector; these include:

- Technology innovation;
- Conservation—demand side;
- Population/migration;
- Electrification of transportation;
- Energy demand related to extreme weather events;
- Extreme events' impact on infrastructure, especially in context with co-stressors;
- Unintended consequences of adaptation;
- Transmission line temperatures.

Modeling framework and capabilities

The model framework conceived by the group (Figure B-1 reflects the complex interactions between energy and water, as both are affected and linked by climate, population demographics, technology development, and policy.

A distinguishing feature about the modeling framework is that it acknowledges environmental and energy regulations that can influence water temperatures, air emissions, protection of assets, and electricity costs that currently serve as uncertainties in most analyses of the energy-water nexus. The framework also relates several feedback loops. For example, business and industry impacts affect demographics and migration, which may in turn affect electricity loads and put pressure on other resources affecting the energy sector (e.g., land use and water availability).

As part of the exercise, the breakout group brainstormed numerous capabilities needed to identify stressors and integrated infrastructural risks arising from evolving vulnerabilities to water-cooled thermoelectric generation. While some of these capabilities exist, the challenge is determining the appropriate coupling of the various system networks, as well as identification of the important spatial and temporal scales. The capabilities identified were categorized under the following classes:

- Operational (e.g., unit commitment and dispatch);
- Planning (e.g., long-term investment);
- Market (e.g., market uncertainties and marginal costs);
- Predictive (e.g., forecast electricity demand, capital forecast, projections of primary fuel supply and costs);
- Drivers (e.g., population demographics, economic growth, climate and extreme weather events);
- Constraints (environmental controls, policy and regulatory environment, existence of energy, water, and natural resources.

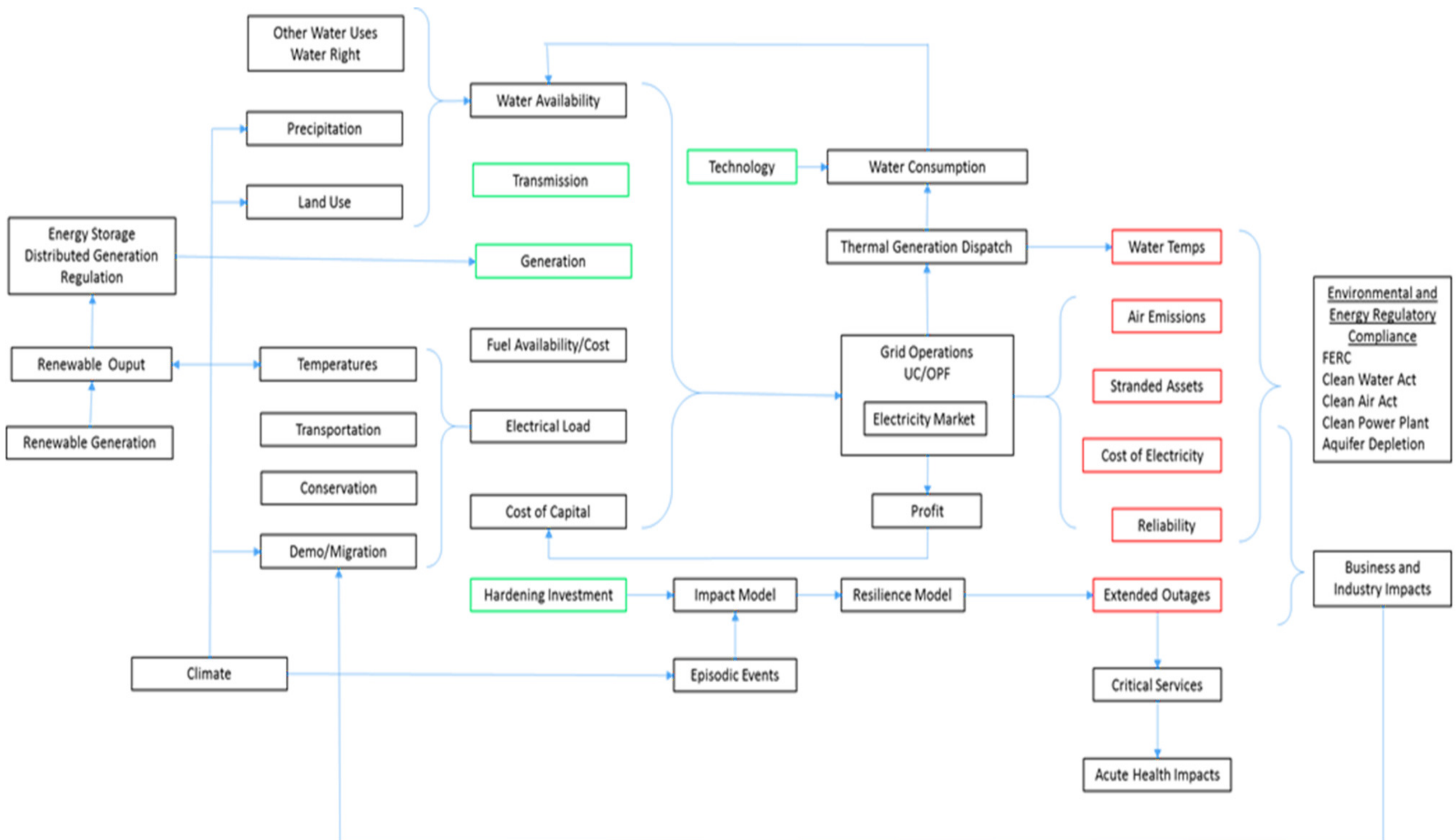


Figure B-1. Modeling framework concept for addressing electric system reliability and demands affected by water quantity and quality. (FERC = Federal Energy Regulatory Commission)

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B.2.2 Health services affected by cascading infrastructure failures and interdependencies, Co-leads: J. Balbus (NIH) and C. Barrett (Virginia Tech)

Problem framing

The Intergovernmental Panel on Climate Change and the Third U.S. National Climate Assessment have both identified cascading system failure as a serious but not well understood threat from climate-change-driven extreme events. This breakout group grappled with the health threats that could emerge from climate-related extreme events when they disrupt necessary medical facilities, increasing morbidity and mortality, disease outbreaks, inability to manage in-need individuals, loss of connection to medical record servers, and other multiplier effects from medical system failures and related drivers. The group explored whether microsimulation models can be used in conjunction with Earth system and infrastructure models to anticipate potential failures and explore development of more resilient health systems and facilities.

User perspective and needs

The breakout group identified a user typology for this example case. The following are some of the different types of users confronting this challenge:

- Public health departments, both state and local, that would like to better understand the vulnerabilities in order to help inform adaptation measures that can protect residents from future health risks;
- Emergency management officials who manage patient flows and hospital operators, both of whom would like to be better prepared for emergency response;
- Private institutions such as CEO risk managers and boards;
- Planners spanning different sectors such as urban planners, emergency planners, and policy makers;
- International adaptation financial mechanisms such as the Green Climate Fund that could be used to increase resilience of health infrastructure in developing countries; and,
- National security officials, to anticipate where health infrastructure failures could occur internationally and thus affect U.S. national security through trade, migration, and immigration.[5]

Prior to the workshop, the National Institutes of Health hosted a webinar on *Cascading Systems Failure and Healthcare Facilities* that helped to identify some of the research and modeling that has been done on the subject to date. One webinar participant noted that while city and regional officials are often consulted about hospital emergency plans, the decisions made about patient evacuation are usually made at the individual facility level. Research suggests that response to dangerous heat waves differs across cities and depends on cultural and other factors. Studies are underway to understand emergency preparedness for critical infrastructure failure during extreme heat events and how individuals make decisions to implement response measures. Other work focuses on dependencies of healthcare and public health on critical infrastructure such as the power sector. How vulnerable are healthcare facilities to large-scale

[5] (1) USGCRP (2016). Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N.Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J.Trtanj, and L.Ziska, Eds. U.S. Global Change Research Program, Washington, DC. 312 pp. dx.doi.org/10.7930/J0R49NQX;(2) CCSP (2008). Analyses of the effects of global change on human health and welfare and human systems. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Gamble, J.L. (ed.), K.L. Ebi, F.G. Sussman, T.J. Wilbanks, (authors). U.S. Environmental Protection Agency, Washington, DC, USA.

cascading power failures, cyberattacks, and severe weather?[6] The Department of Homeland Security's Office of Cyber and Infrastructure Analysis and National Infrastructure Simulation and Analysis Center (NISAC) are focusing on: (1) strategic analysis, (2) infrastructure prioritization, (3) operational analysis, and (4) capacity/capability development. They work closely with the U.S. Department of Health and Human Services on healthcare infrastructure protection. Some groups are conducting probabilistic modeling to evaluate the seriousness of the issue.

The group identified a number of specific health outcomes/modeling outputs of interest, including overall mortality; injury-related mortality; heat-stroke mortality; emergency room admissions for injury; heart attack; renal failure; and heat stress and heat stroke. A finding based on the needs of all of the users addressing cascading health-related system failures is that information is needed about both short-term disaster response planning, as well as long-term investments in resilience infrastructure, for example in energy, communications, and technology.

Drivers

Cascading systems failures following extreme events are inherently multi-causal. The breakout group pointed to several factors that influence healthcare systems failures: (1) electric grid load damage; (2) ability of healthcare facilities to disconnect from grid/supply needs; (3) communications systems function/damage; (4) ability of healthcare facilities to access other means (satellite, etc.) of communications; (5) flooding of roads and critical infrastructure/connections; (6) epidemiologic risk assessment of health burden from event; and (7) epidemiologic risk assessment of health burden based on estimates of baseline prevalence of conditions and needs for ongoing care and monitoring.

Modeling framework and capabilities

Modeling studies of infrastructure impacts typically examine system failures up to the point of reaching the walls of healthcare facilities but seldom address the unique vulnerabilities and impacts on health from loss of critical services to healthcare facilities in any detail. However, there are new modeling efforts and capabilities in this area that could help approach this problem. Some of these are listed below:

- Use of simulated future climate-change events to examine how environmental conditions (e.g., flooding and heat) and potential resulting infrastructure deterioration impacts health. New work is using high-resolution climate downscaling and considering the effects of the built urban environment on heat islands and even how mean temperatures and extremes interact with infrastructure deterioration to simulate indoor environments and health impacts. Behavioral data is being collected via survey, interviews, and remote sensing. Researchers hope to better understand how individuals respond to extreme heat events, particularly coupled with a regional blackout. While facilities are not included in the study, their model could be applied to include facilities as well.
- Other work has mapped and developed "service areas" that help estimate disruptions and consequences of power failure on hospitals in large areas. Power outage modeling before major storms is being provided to help inform response planning prior to the storm. Modeling of healthcare facility supply chain vulnerabilities is also being developed.
- A new modeling effort focuses on the Eastern seaboard and the Gulf Coast using a comprehensive database of 140 acute care hospitals in the region and assigning common attributes between built

[6] Kenward, A. and U. Raja (2014). Blackout: Extreme Weather, Climate Change and Power Outages. Climate Central. Available at http://assets.climatecentral.org/pdfs/PowerOutages.pdf.

environment elements in order to identify specific vulnerabilities to extreme health and flooding. Researchers hope to model patient movement once the model is complete.

- Another model was described that focuses on Hampton Roads, VA and models storm scenarios to help identify vulnerabilities. Better information on local populations, which include many uninsured individuals, is needed, so modelers have developed a methodology to gather additional information on "dimensions of vulnerability," including medically fragile populations, evacuation potential, and shelter-in-place capabilities. Before a major event, potentially displaced populations and their needs ("dimensions of vulnerability") can be modeled and mapped. This can help estimate the demand on surviving institutions. Researchers also test intervention effectiveness to determine the value and potential benefits of a large investment in facilities hardening.

The breakout group conceived a modeling framework (Figure B-2) that considers the needs for healthcare services, as well as impacts on facilities that supply these services. Demands for healthcare depend on a variety of factors including those that determine the baseline health of different user groups (e.g., pre-existing health conditions, nutritional status, exposure to environmental health stressors, etc.) and the needs of different groups in acute situations such as natural disasters. The framework must be able to model the impacts of longer-term events and conditions (e.g., droughts, prolonged heat waves), as well as shocks such as storms and floods, on demands for healthcare services. Healthcare infrastructure modeling should consider (1) fixed-location facilities, including both on-site clinical services and on-site community services, and (2) mobile or decentralized facilities that comprise offsite clinical services and emergency response (see modeling framework concept in Figure B-2). This part of the modeling framework needs to consider influences of potential failures across several sectors including energy, water, communications, transportation, security, to name a few.

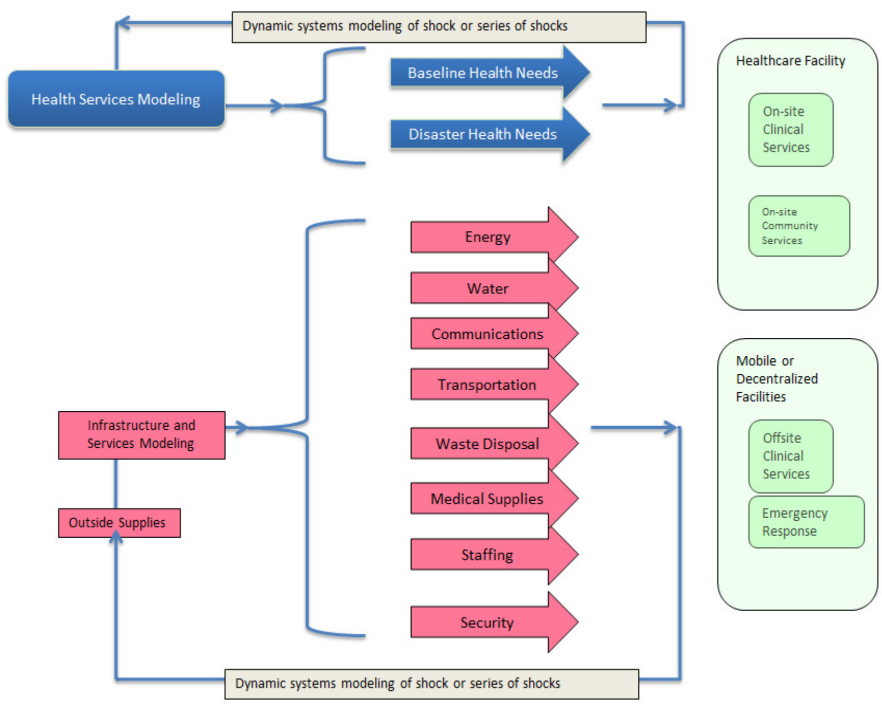

Figure B-2. Modeling framework concept for addressing health services affected by cascading infrastructure failures and interdependencies.

Participants noted that while the workshop has an infrastructure focus, thinking about social sector intersections with the hard health infrastructure and how behavior changes demand is an important area to grow. There was also a suggestion to have a framework that identifies the connections between localized information and generalizable information. This reflects a recognition that there are commonalities among cities, but also that each city's population has unique patterns of illness, behaviors, risk perceptions, and needs. Defining what is common, but also providing a way forward to identify methodologies and approaches to systemically gather an understanding of what is unique in each city/region, would be an important contribution.

B.2.3 Coastal city inundation affected by sea-level rise and extreme weather events, Co-leads: C. Covel (DHS) and A. Abbas (University of Southern California)

Problem framing

Cities across the United States are becoming more vulnerable to flooding events for a number of reasons, including, but not limited to: overdevelopment (nowhere for the water to go), development in flood plains, rising sea levels, and extreme weather events. In many U.S. coastal cities, critical infrastructure is within areas that are more likely to be flooded with increasing sea-level rise and storm surge.[7] For example, some of the nation's largest ports are along the Gulf Coast: these are especially vulnerable due to a combination of sea-level rise, storm surges, erosion, and land subsidence.[8] Many military installations are also located along the East and Gulf coasts. Coastal flooding can affect a myriad of city infrastructure and networks, such as transportation services, water, energy, and communications—all in the same geographic vicinity and with compounding impacts. The question addressed by the breakout group was: *What steps can cities take to plan and prepare for the future, and most efficiently mitigate the risk of these events?*

The breakout group considered a number of specific metrics that would help clarify the potential scope of future impacts on coastal cities without adaptation and mitigation measures. These include: (1) frequency and magnitude of flooding events; (2) damage estimates to potentially include physical damage costs, lives lost, loss of economic output, and insured losses; (3) cost of flood mitigation measures; (4) and change in damage estimates with and without mitigation measures in place.

User perspective and needs

The breakout group explored information needs through the lens of state and city planners, land use regulators, and owners and operators of infrastructure. Examples of questions concerning city managers include:

- How should we allocate population growth to sub-city zones?
- How will distribution be affected by intervening disasters?
- How should we allocate utility lifetimes by city zones according to projections of population or income using a reduced form/quick-and-dirty approach?

While IAM assessments focus primarily on long-term impacts, looking out 50 or 100 years, cities, states, and the Federal Government are very concerned about cascading system failures arising from climate-related extreme events such as flooding. These kinds of events are what climate models are projecting we

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[7] Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, B. Solecki, and L. Toole, 2012: Climate Change and Infrastructure, Urban Systems, and Vulnerabilities. Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. 119 pp., Oak Ridge National Laboratory. U.S. Department of Energy, Office of Science, Oak Ridge, TN.

[8] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

could expect to see more of in the next few decades.[9] The Department of Homeland Security, for example, looks at present conditions in addition to looking forward. This breakout group therefore highlighted the importance of models to be scalable to fit the time horizon needs of the particular application.

Generally, there are two types of time horizons relevant to the set of users identified by the group: There are medium- and long-term planning exercises such as land use planning, codes, buildings, zoning, and insurance; and short-term preparedness/emergency response planning, such as evacuation planning and situational awareness. These time scales are relevant because city and state planners need to develop a plan to evolve their cities in an economically sound way that mitigates flooding risks.

The group also came up with a typology of questions of interest to these users, namely questions about:

1. Hazards—How will inundation frequency, intensity, and duration depend on current infrastructure?
2. Growth patterns—How to move from the current distribution of infrastructure to future distribution of infrastructure (and population)?
3. Damages—What endpoints should we focus on to characterize impacts? The group brainstormed six endpoints:
    a. Deaths/morbidity (as risk ratios for different segments of the population);
    b. Building damage (building demography plus depth damage functions expanded to different classes of buildings often found in cities such as high rises);
    c. Infrastructure loss of function, which links to other infrastructure analyses but incorporating flooding stressors related to:
        i. Communications
        ii. Water
        iii. Wastewater
        iv. Transportation
    d. Population displacement, which is both a long-term and short-term process—short-term evacuation prevents immediate death from direct effects and long-term evacuation is a result of different processes (total destruction, better opportunities elsewhere, etc.);
    e. Loss of ecosystem services;
    f. Disruption of social networks;
4. Resilience—How to encapsulate and quantify resilience given 1 and 2 by (a) focusing on reducing adverse endpoints in 3, and (b) considering hastening time to restoration of ‘pre-shock’ baseline conditions.

Participants suggested that the frequency, intensity, and duration of these endpoints are conditional on the distribution of the infrastructure (return frequencies).

Drivers

The group co-leads proposed three dominant drivers/influences of coastal city inundation from sea-level rise and extreme weather events: (1) urbanization and land use patterns; (2) infrastructure design; and (3) changes in sea level and climate factors in inland/fluvial flooding.

[9] Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Modeling framework and capabilities

Similar to the previous two breakout groups, this breakout group focused predominantly on the modeling of disruptive events and cascading failures, or what was referred to as "knock-on effects." In this regard, city and state planners are not only interested in learning about the potential cost of cleanup, repair, and/or replacement of infrastructure following a disruptive event, but also the economic, social, and environmental effects. Major floods can disrupt supply chains, suspend economic activities, and threaten the well-being of coastal communities. Given that the knock-on effects that may arise from climate-related coastal flooding stem from both physical and social factors, the breakout group conceived a modeling framework (illustrated in Figure B-3) that is informed by both projections of the evolution of the physical system (local sea-level rise and storm incidence), as well as the evolution of the human system (e.g., spatial distribution of population and demographics), both at fine scales. The confluence of these physical and human system characteristics inform the metrics city and state planners care about: mortality and morbidity, building damage, infrastructure loss of function, short-run population displacement, and long-run population migration or location preference. These inform the knock-on effects of coastal city inundation and could also provide information about the costs of inaction, or inversely, adaptation, including co-benefits of adaptation options taken.

Importantly, the group highlighted that by identifying the decisions that we are trying to inform, we also realize the kinds of models that are needed to identify the knock-on effects and their potential costs. For example, one could ask: given certain assumptions about economic development, what hydrological modeling is needed?

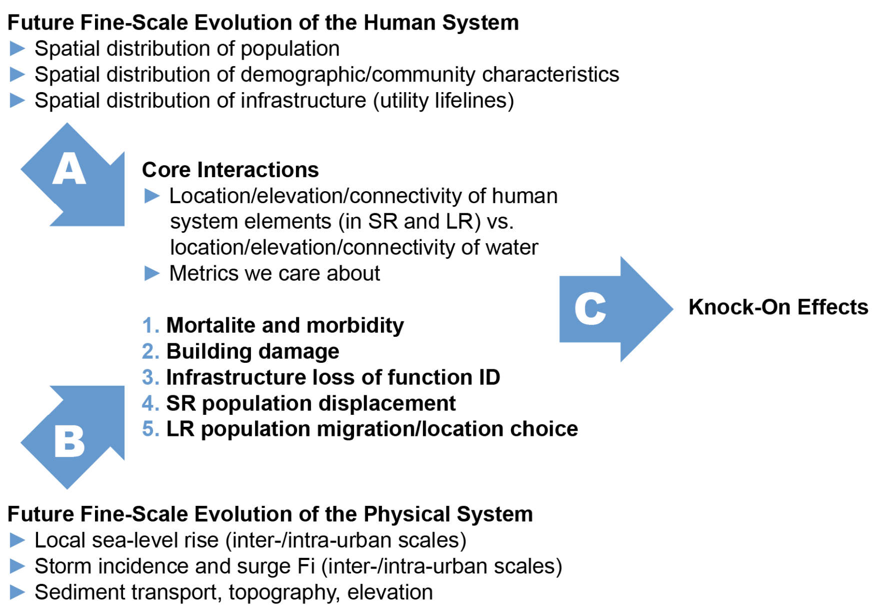

Figure B-3. Modeling framework concept for addressing coastal city inundation affected by sea-level rise and extreme weather events.

Among some of the modeling and data needs the breakout group identified was a Digital Elevation Model for coastal cities, although a participant noted that LIDAR is available in raw form in a variety of states. The Department of Homeland Security is interested in broad-scale impacts with less specificity of infrastructure, as they already have tools to overlay critical infrastructure locations onto impact maps. Also of particular interest was a coastal inundation model at the county level developed by James Neumann and his team at Industrial Economics, Inc. They have conducted studies linking a tropical cyclone simulation model with a model of storm surge to assess economic damages, cost-effective adaptation options, and effects of global greenhouse gas mitigation policy using the Environmental Protection Agency's (EPA) National Coastal Property Model across the coastline of the contiguous United States.[10] There was agreement that we need some sense of where people will be in the future. Although the number of people may not be possible to assess with fine granularity, spatial consideration can be tackled. In general, the group also highlighted the importance of using or developing capabilities that are scalable.

B.2.4 Urban socioeconomic systems and vulnerable communities affected by heat waves and air-quality events, Co-leads: J. Li (EPA) and J. Rice (Smarter Decisions, LLC)

Problem framing

Population growth and associated infrastructure development, land use change, and economic activities influence the climate (e.g., ambient temperature and humidity) and air quality (e.g., ground-level ozone) of cities. Urbanization and infrastructure development patterns can produce local air pollution "hot spots" and "heat-island effects" where built-up areas have warmer ambient temperatures than the surrounding natural land cover. The heat-island effect raises demand for air conditioning, as does the climate change trend overall, which may or may not be able to be met by existing infrastructure. All of these factors form complex interactions between pollutant emissions (e.g., aerosols), climate change, and air quality. Climate and air-quality dynamics, interacting with urban socioeconomic systems, impact urban vulnerabilities and public health. Given this backdrop, the breakout group discussed needed capabilities for addressing the following question:

> *How may Federal air-quality regulators evaluate future policy options to protect human health and minimize implementation and compliance costs, while also ensuring that important influences from complex multi-sector and multi-scale interactions are addressed (e.g., climate change, urbanization)?*

While capabilities to model health impacts from air quality are well developed (e.g., EPA's air quality and human health modeling systems), and there are also improved modeling capabilities to better understand the interactions between climate change and air quality, there is a recognition that integrated modeling of human systems, climate, and air quality is needed to fully understand health-related vulnerabilities and outcomes. The breakout group posited that impacts occur on a human scale, both acute and chronic, and are driven by interacting systems/sectors that operate across many scales and evolve over time. Integrated modeling would enhance the evaluation of the impacts, costs, and benefits of mitigation and/or adaptation strategies at these finer scales.

The breakout group pointed to four outcomes of interest to address this particular problem:

1. Characterization (frequency, duration, intensity) of heat-wave and air-quality events;
2. Estimates of vulnerable populations and health impacts (mortality, morbidity);
3. Economic costs associated with the impacts (welfare, value per statistical life);
4. Costs and benefits of response (mitigation and adaptation) strategies.

[10] See: Neumann, J. E., Emanuel, K., Ravela, S., Ludwig, L., Kirshen, P., Bosma, K., & Martinich, J. (2015). Joint effects of storm surge and sea-level rise on U.S. Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy. Climatic Change, 129(1-2), 337-349.

User perspective and needs
Decisions made about infrastructure investment across several sectors and at different scales, in addition to sector interactions, ultimately affect local air quality and health impacts. A distinctive aspect of this problem is that the combined impacts do not affect a population equally. The most vulnerable populations to the impacts of heat stress and air quality are the elderly, young children, low-income populations, people who work outdoors, and people in poor health. Thus, improved capabilities for understanding how different demographics and other human system characteristics (e.g., socioeconomic and institutional factors) interact with climate change and air quality are needed.

This problem, the breakout group recognized, is multi-scaled. In particular, the breakout group identified four major decision contexts:

1. Federal/regional air-quality regulators;
2. Federal/local public health regulators;
3. Regional/local regulators and planners;
4. Emergency and preparedness responders.

Federal agencies set regulations and use IAMs, air quality, and other models, but cities and local entities do the implementation to meet these regulations, and are the ones being impacted by the combined physical and social effects. The breakout group thus suggested that it might be more relevant to expand capabilities to look at impacts at the level of census blocks.

The breakout group also attempted to articulate more specifically why integrated modeling is necessary for this problem. A key question being asked is "*what is an average person's exposure to the combined impacts of air quality and heat stress.*" Although EPA has overlaid Census and air-quality maps to explore this question, they do not account for population movements during the day and through time. Thus, to answer this question, multi-scale and multi-sectoral integrated models are needed. Breakout group participants also highlighted how several Federal, state and local agencies are working on transportation, building codes, health services, and other areas for which information on the interactions of air quality and heat stress would be useful.

Drivers
Changes in population, land use, urbanization and associated infrastructure development affect both air quality and regional climate in urban areas, which also have implications on health, outdoor activities, and economic productivity. Reflecting the complex interactions between these systems, which also span multiple scales, the breakout group identified three categories of drivers relevant to this problem:

1. *Socio-economic*, e.g., population growth and spatial distribution, rural-urban land use change, rate of urbanization, technological change;
2. *Institutional*, e.g., land use planning and regulations, funding, environmental policy, such as air-quality standards;
3. *Exposure and human health vulnerability*, e.g., income and income distribution, demographics (e.g., age distribution), healthcare provision and quality, early-warning system effectiveness, emergency preparedness, physiological adaptation.

Modeling framework and capabilities
This example illustrates the relationships that exist between global/national-level changes, such as population, land use and urbanization, and regional/local-level impacts and responses, such as local air pollutants, heat-island effects, and institutional factors that together produce vulnerabilities, adaptive

capacity, and morbidity and mortality at the individual scale. The concept for the modeling framework that the breakout group developed (depicted in Figure B-4) shows the complex relationships among the following systems/sectors:

- Demography (population growth, migration, age distribution, etc.);
- Economic growth;
- Land use change;
- Urban infrastructure (buildings, building codes/HVAC capacity, transport, green space, etc.);
- Transportation fuels;
- Electricity generation/air emissions;
- Air quality (particulates, ozone, etc.) ;
- Climate and weather;
- Epidemiology;
- Public health resources (e.g., warning systems, emergency plans, heat shelters, healthcare provision).

Starting on the left side of Figure B-4, the framework shows how global-to-regional-scale changes in climate (modeled by ESMs) and, ultimately, local air quality, are driven by changes in human systems (modeled by IAMs), such as transportation, energy, population, urban form, and so on. The diagram also notes that each of these modeling paradigms is driven by assumptions on policy, technological change, resource availability, and socioeconomics, but it does not try to represent this detail. In the center of the figure, the diagram shows that the combination of climate and human-system influences affect hazards and vulnerability at the local and individual scales (modeled by IAVs). Finally, the right side of the diagram lists the societal metrics of interest such as mortality and morbidity, economic/infrastructural costs, welfare, co-benefits in other sectors, and potential feedbacks. Note that the diagram shows that heat waves and air-quality concerns alone do not lead to mortality and morbidity, but are a result of socioeconomic factors and adaptation responses combined with exposure from these impacts. The breakout group suggested that although a meta-system invoking high-fidelity models in each sector will be unwieldy and computationally excessive, especially for uncertainty and risk analysis, we should not overlook important forcings and interactions.

In Figure B-4, each icon and arrow represents a desired modeling capability. Currently, we have well-developed statistical air-quality and health-impact models. There are also some promising modeling work and research on the heat-island effect. For example, participants cited two modeling efforts, one at MIT[11] and another at the University of New York, that examine the heat-island effect and are well developed for their locations. However, the group argued that an improved understanding of second-order effects of climate change on air quality (e.g., wildfire) is needed. The group also noted that we have weak or underdeveloped modeling capabilities for capturing the interactions shown in the diagram, certain adaptation measures (e.g., self-treatment), and behavioral changes. In addition, downscaled climate models do a poor job of representing heat waves. Thus, analytic efforts connecting climate and weather models would be beneficial.

The breakout group also pointed to the importance of addressing uncertainties in the framework, in particular, uncertainties in downscaled climate projections, air-quality hot spots at urban scale, and

[11] See for example, http://web.mit.edu/mit-mi-cp/research/projects/flagship08.html.

projections of extreme events. There are also uncertainties in the transportation and technology space. One participant asked, how might electric vehicles affect the future, for example?

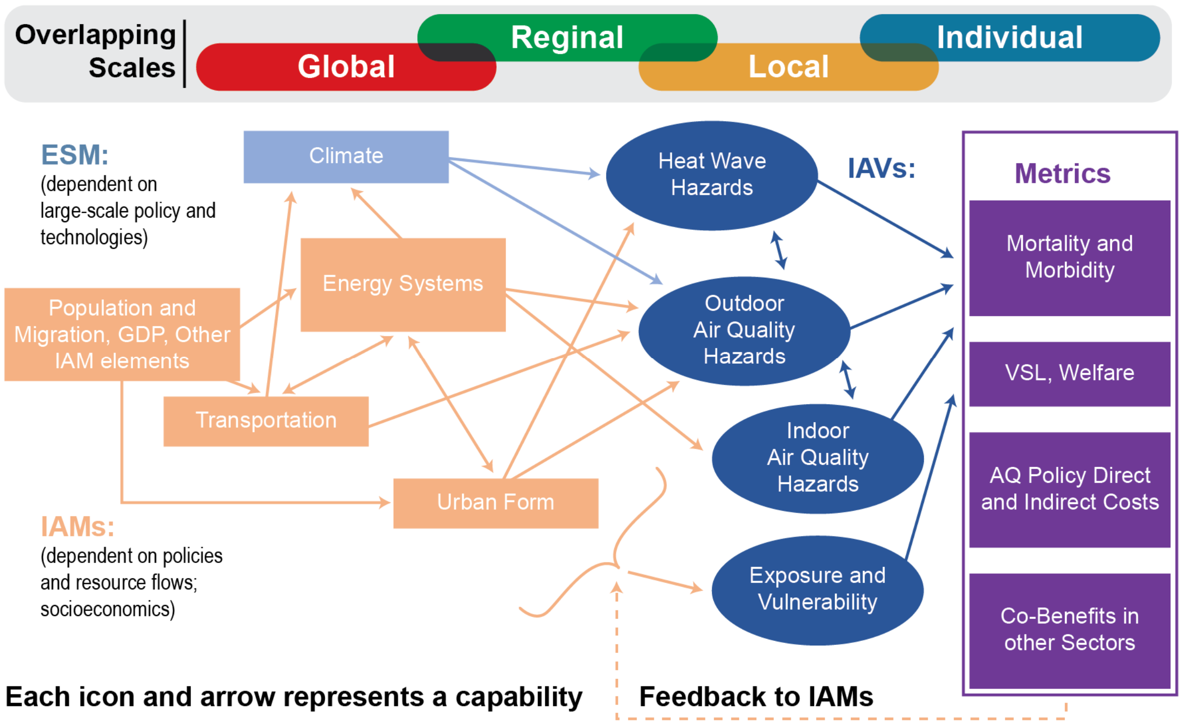

Figure B-4. Modeling framework concept for addressing urban socioeconomic systems and vulnerable communities affected by heat waves and air-quality events.

Finally, the breakout group discussed data needs. There are many data gaps related to built infrastructure, particularly outside of the top 25 largest cities. Participants pointed to emerging forms of data (e.g., real-time inputs) that are promising and could enhance models to look at multi-scale impacts, but also cautioned that the models need to be flexible to allow for this. Agent-based modeling has great potential, but there is a question of how to make these models consistent with larger-scale models in an integrated modeling framework. Also, simply including human beings in the models, participants agreed, does not result in improved modeling capability. To illustrate this point, the group asked: Are people making decisions based on the right information? Are human behaviors in simulation models realistic? One suggestion was the use of crowd-sourced data for some inputs, as government agencies do not have the bandwidth to collect this information.

B.3 Integrated Themes on Drought and Increased Variability of Water Supply

B.3.1 Reservoir resilience affected by droughts, floods, and changing extremes, Co-leads: K. White (USACE) and P. Reed (Cornell)

Problem framing

Floods and droughts are intimately connected. How can reservoir operations and the competing multi-sector demands that depend on them better balance increasingly extreme floods and droughts? How will the challenge of meeting these competing demands change over time? Answering this question is challenging, given changes in demands, infrastructure, land use, environmental regulations, and institutions governing water allocation, and given the interaction of all of these with changes in climate that are increasing the frequency and severity of drought in some of the same locations experiencing very heavy precipitation events. The question is far from academic; it is a challenge being confronted by Federal agency program managers, state water agencies, cities/counties, regional water managers, river basin commissions, and others, as they make decisions required to meet seasonal water demands as well as develop plans for long-term stewardship of resources. See Figure B-5

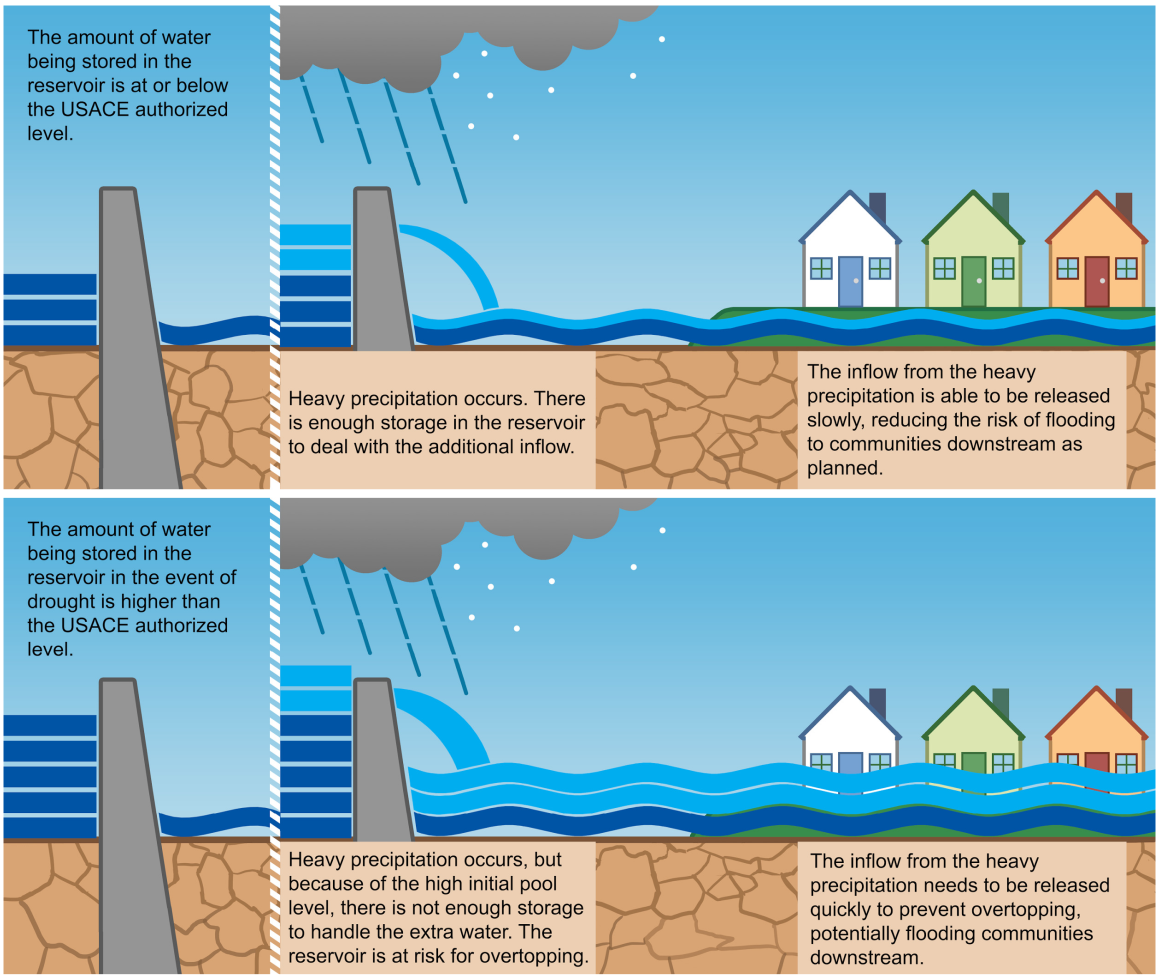

Figure B-5. Risks faced by water managers from increased frequency and intensity of drought and heavy precipitation events.

User perspective and needs

This breakout group explored the information needs of state and city planners and engineers, and owners and operators of water resources infrastructure as they seek to manage water quantity and quality issues, as well as emergency managers contending with implications of flooding. The objectives of these groups is to maintain reliability and manage costs of supplying water in sufficient quantity and quality to meet a changing demand profile, one increasingly affected by demands for energy production (including to supply water management) while simultaneously preventing flooding during wet season rains. The changing hydrograph, with increased flows in spring and early summer and more intense drought in late summer and early fall, presents challenges to both objectives. Different decision makers within this broad set face different types of decisions, from decisions about release and flow management during the annual water calendar, to zoning and other land-use decisions that affect imperviousness and runoff, to longer-term decisions about infrastructure investments.

The group identified a number of specific metrics that decision makers could use to help inform decision making and planning related to the resilience (i.e., preparedness, ability to absorb disruptions, and recovery or adaption to disruptions) and robustness (i.e., maintaining high levels of performance and reliability across many possible futures) of reservoirs. They noted that the decisions depend on the interplay between short-term management (e.g., operations, resource conservation, pricing policies) and long-term planning (e.g., storage allocations, new nature-based or hard infrastructure options). Additional metrics identified as being useful intermediate outputs included measures of opportunity costs or regrets for maintaining status quo operations; risks and benefits of alternative operations and resource allocations; spatial and/or temporal mappings of key system constraints, impacts, and adaptation benefits; uncertainties and tradeoffs in measures of the economic and engineering performance measures for impacted sectors (e.g., financial stability, reliability, resilience, vulnerability, mortality, equity, efficiency, etc.).

Drivers

The group sorted through a wide range of uncertain factors that influenced the nature of the problem and that would need to be incorporated into modeling that addressed all aspects of the affected water supply and management systems, including: (1) climate-impacted hydrology affecting floods and droughts; (2) changing land use that impacts runoff; (3) changes in water conservation or demand management that decrease water demand; (4) scale-up of renewable resources, including hydropower, and other energy market impacts that could result in increased or decreased consumptive use of water in energy production; (5) demographic changes that alter water demand; (6) changes in national priorities that affect natural resources management, and (7) institutional, governmental, or organizational ability to balance competing needs.

Modeling framework and capabilities

Given this wide-ranging list of drivers, members noted the importance of bounding the system to focus on the key uncertainties for any given question or problem, thus keeping the modeling challenge more tractable. The group did not develop a specific conceptual framework to quantify metrics under different assumptions and configurations of infrastructure, land use, and other factors. They focused on identifying a set of capabilities (models that represent key drivers/influences, data sets, decision-support tools) that would be required for such a framework. These capabilities are included in Table B-1.

Table B-1. Capabilities required for a modeling framework addressing reservoir resilience affected by droughts, floods, and changing extremes.

Describe required knowledge/capability (include specific systems, processes, interactions)engineering performance measures	Is the capability currently available or does it require additional development?	Statistical, physical process, or hybrid model	Temporal Resolution(s)	Geographically explicit? (include spatial resolution)
Hydroclimatology	Moderate	Hybrid	Hourly to decadal	10s kms
Groundwater-surfaces interactions (quantity and quality)	Weak to moderate	Hybrid	Hourly to decadal	m to 100s kms
Demand-side (conservation) modeling	Weak to moderate	Statistical, physical process, or hybrid model	Hourly to decadal	Basin scale
Regional development , scenarios and stressors	Weak	Hybrid	Decadal	Basin to state
Decision-support processes and contexts	Emerging	Hybrid	Annual	Households to US
Institutional / governance constraints	Emerging	Behavioral, process-based, statistical, hybrid, agent-based	Annual to decadal	Town to US
Reservoir operations	Moderate (in short-scale) Weak (long-term)	Hybrid	Hourly to seasonal	Single to system
Reservoir allocations	Moderate	Hybrid	Seasonal to decadal	Basin to national region

B.3.2 State economies, including agriculture, affected by drought, Co-leads: R. Sands (USDA), A. Ruane (NASA) and K. Fisher-Vanden (PSU)

Problem framing

Drought events are highly disruptive to human systems, with water shortages affecting agricultural production, industrial production, energy production, municipal use, river transportation, and environmental services. Under the sudden onset of drought conditions, farmers are faced with the choice of finding alternative sources of water to irrigate crops or withstanding lower yields. A farmer's short-run strategy during drought is to pump groundwater, but that becomes increasingly expensive for a drought that lasts more than one year. With before-season warning or observation of an ongoing drought, farmers may also adjust land-use practices (e.g., through alternate crops, modified irrigation strategies, or fallowed fields) to reduce risk. Multi-year or higher-frequency droughts place additional pressures on scarce groundwater resources. Over many years, farmers may adapt to drought conditions by changing to drought-resistant crops or more water-efficient methods of production.

The economic impacts of droughts are buffered by several mechanisms. Farmers may protect against drought risk by purchasing crop insurance before the season or applying for disaster relief following an event. At the national level, drought in one region may improve the economics in another region through higher agricultural prices, an effect that may be buffered depending on existing commodity stocks. Consumers and intermediate users (e.g., livestock producers) may adjust to a decrease in output in one region by substituting for higher-priced commodities from other domestic or foreign sources. Drought affecting bioenergy crops also has the potential to affect energy supply, and hydroelectric, nuclear, and traditional power generation facilities rely on water resources for energy production and facility cooling. Previous droughts have also driven changes in state, county, and city policies on municipal and industrial water use. In some regions, legislation also mandates an amount of water that must be passed through ecosystems. These anticipated economic effects inform Federal and state efforts to help mitigate and adapt to drought events.

Reflecting that the impacts of drought on state economies spans multiple sectors and spatial scales, the breakout group presented the following question: *What are the impacts of drought on state economies accounting for interactions and feedbacks across sectors and regions, and trade responses?*

User perspective and needs

The breakout group addressed the question from the perspective of Federal and state agricultural agencies that provide conservation planning assistance through research and outreach services, as well as support disaster relief programs. At the national level, several USDA offices, including the Farm Service Agency and the Risk Management Agency, fund efforts to help prepare farmers for drought events and offer crop insurance. The National Institute of Food and Agriculture funds foundational agricultural research and a risk management education program. Programs within the National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration also help monitor agricultural development and identify drought-affected regions. The economic effects of drought are relevant to such agencies to help them: 1) understand the potential economic losses from drought; 2) fund research and outreach efforts to help farmers limit the impacts of drought; and 3) structure economic relief programs to maintain a healthy agricultural sector without introducing moral hazard. Drought also affects a range of private industries involved in commodity chains (food, fiber, and energy) and agribusiness suppliers (seeds, equipment, etc.). In addition to the agricultural sector, water-stressed conditions increase the competition for water resources among agricultural, industrial, energy, municipal, transportation, and environmental stakeholders.

Stepping into the shoes of these users, the breakout group identified multiple specific metrics or desired user-driven outcomes from a modeling/analytic assessment of the impacts of drought on state economies. These include:

- Change in welfare and distributional impacts of drought, and short-term drought intervention and long-term adaptation measures to address these impacts under various scenarios;
- Economic resilience under different drought scenarios—sensitivity analysis (vulnerability);
- Characterization of drought events (frequency, duration, intensity, extent);
- Water availability;
- Cost of intervention technologies (e.g., irrigation; desalination; low-flow shower heads);
- Loss of agricultural output/revenue;
- Loss of electricity generation (output and revenue);
- Loss of industrial output/revenue;
- Impacts on employment;
- Basic economic indicators;
- Water transport/navigation;

- Impacts on recreation/tourism;
- Land use;
- Cost of capital;
- Environmental damages (e.g., ecological impacts, fish population, water quality);
- Subsidy outlays.

This problem inherently spans multiple spatial, temporal and sectoral dimensions. Spatially, there is local/state with national and global feedbacks. There are also multiple time steps—for example, daily for crop process models, monthly for hydrology, and annually for economic models. The problem is also multidisciplinary, for example, incorporating information from climate science, hydrology, agriculture, and economics. Lastly, the group mentioned the modeling complexity aspect of this problem (breadth versus depth).

Drivers

Although the group sorted through a number of drivers that influence the problem, they highlighted three categories of drivers in particular that would need to be incorporated into modeling analysis on the interplay of drought and its impacts on state economies. These are:

1. *Climate (from historical analogs or climate models)*—The group pointed to the current drought in California as a potential valuable recent example, in addition to droughts in Texas (2011), Colorado (2003), and the Upper Midwest (2012).
2. *Hydrology and soil type*, as landscape properties influence water retention, run-off, and crop suitability.
3. *Land use decisions and economic adaptation*—for example, changes in planted and harvested areas for various crop types and management systems may be projected through agricultural economic models and will affect other elements of the system.

Modeling framework and capabilities

The conceptual diagram of a modeling framework proposed by the breakout group (Figure B-6) shows the complex interplay between physical and societal factors and constraints on water availability for different uses in the economy. The GCMs provide inputs to hydrologic models that provide higher-resolution information on water supply, which in turn inform water management/allocation. Allocation of water into the different segments of the economy demanding water (e.g., agriculture, power generation, and industry) are contingent on a wide range of dynamics that the breakout group identifies, including regulations, infrastructure, technology, reliability, demographics, etc. In parallel, changes in economic conditions, (e.g., related to welfare, land use, intra- and international trade, and water resources and conveyance) influence all three: water supply, water management, and water demand. Then, depending not only on physical exposure of the different segments of the economy to drought, but also other considerations such as vulnerability, response interventions, planned interventions, autonomous adaptation, or under normal or "business as usual" operations, we can derive information on sector productivity and costs, actual water use, and ecosystem degradation.

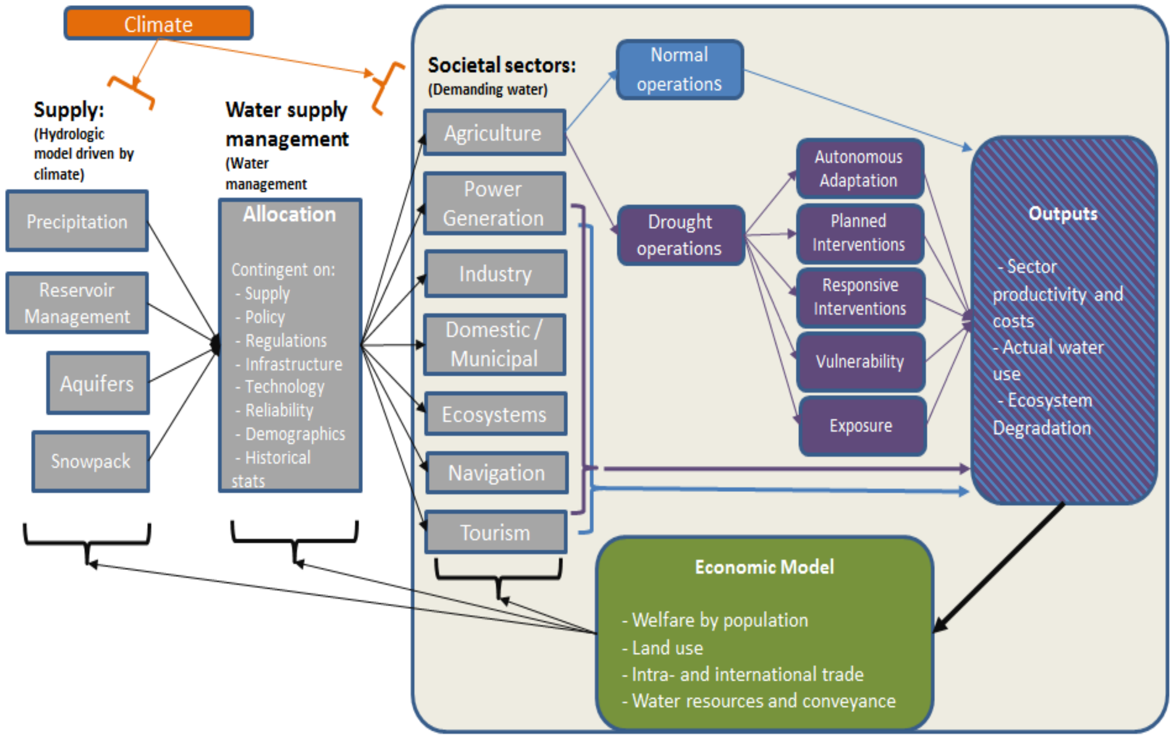

Figure B-6. Modeling framework concept addressing state economies affected by drought.

The group identified several uses for this modeling framework, including helping inform:

- Needed changes in water allocation paradigms (e.g., state water resources board);
- Drought-motivated infrastructure investment (e.g., Army Corps of Engineers, municipalities, private sector);
- Federal mandates related to electricity markets and water quality as a result of water scarcity (e.g., FERC, EPA on stream temperature);
- Risk management (USDA, science community)—e.g., crop insurance. Responsive versus preventive/planned. Will get harder and harder with higher temperatures;
- How to reduce exposure and vulnerability (e.g., agricultural agencies, extension services)—zoning laws, crop subsidies, education;
- Tax revenue base, social services, and general economic impacts (e.g. cities, states, municipalities)—need to forecast future economic effects;
- Municipal water pricing/quotas (e.g., municipal water boards).

In Table B-2, the breakout group provides a list of capabilities that this framework would require, noting in some areas examples of specific types of models or other analytic tools.

Table B-2. Capabilities for integrative modeling of state economies affected by drought.

		Examples of models/tools addressing the required knowledge component needs for this issue and user perspective
Capability 1	State-level economic activity	IMPLAN models
Capability 2	Water supply	WBM
Capability 3	Water allocation	WEAP
Capability 4	Power system response to drought	
Capability 5	Industry infrastructure response to drought	
Capability 6	Municipal infrastructure response to drought	
Capability 7	Ecosystem response to drought	
Capability 8	Navigation response to drought	
Capability 9	Recreational use response to drought	
Capability 10	Agriculture response to drought	Process-based crop models; Schlenkereconometric model
Capability 11	Population growth/migration	
Capability 12	Land use change	
Capability 13	Regional climate scenarios	
Capability 14	Scenario consistency	Scenario consistency
Capability 15	Intra- and international trade	RAPs; cross impact balance analysis
Capability 16	Water conveyance	Global model

B.3.3 Planning for wildfire impacts and management under changing climate, environmental, demographic, and policy futures, Co-leads: L. Langner (USDA Forest Service) and C. Tebaldi (NCAR)

Problem Framing

Although wildfire is a natural process that is necessary to maintain some ecosystems, climate change is, on balance, expected to increase both the extent and severity of wildfire: increasing the annual wildland area burned, increasing the length of wildfire seasons, and altering the structure, function, and potentially the species composition of wildland ecosystems. Increased wildfire risk relates not only to climatic factors but also societal factors. The expansion of human development into wildland areas alters wildland ecosystems through fragmentation and disruption of wildlife habitat and corridors, and also increases wildfire risk and potentially its impacts on human health and welfare and associated infrastructure. Large uncertainties in translating future climate projections into fire risk projections exist, especially at regional scales. Uncertain climate-induced changes in fire occurrence in concert with population growth and associated peri-urban development will exacerbate these problems in the future.

Wildfire risk measures can be used to compile the wide range of wildfire impacts. Impacts on human populations include the need for designing safe evacuation, providing for evacuees, and rebuilding and repairing homes and infrastructure. These responses can impose significant economic burdens that can strain the resources of local, regional, and state governments and response agencies. Health effects from particulates and toxic air pollutants can have both temporary and more long-term effects on residents' health. Ecosystem services important to community residents are often impaired, depending on the level of fire severity. For example, sedimentation from burned areas can impact water quality and associated drinking water supplies.

Given the complex interplay between climatic conditions and societal factors on wildfire, the inherent uncertainties in future impacts on human systems, and needed responses to these impacts, this breakout group focused on the following questions:

1. Depending on the uncertain future evolutions of regional climate and societal factors, how will the ensuing changes in wildfire extent and severity impact the provision of ecosystem services from forests and rangelands, and human health and infrastructure?
2. What adaptation and mitigation measures have the greatest potential for reducing risks and impacts from wildfires?

User perspective and needs

Many users seek information in this area (e.g., firefighting agencies, land management agencies, local government, private landowners, FEMA, and EPA). For this example, the breakout group adopted the user perspective of Federal firefighting agencies. There are Federal land managers who are responsible for fire management on Federal lands and some who are responsible for fighting wildfires on all lands. These managers need to balance allowing wildfire to play its natural role to maintain healthy ecosystems with minimizing risk to human populations and associated infrastructure. The effects of climate change on forest and range ecosystems will play out over long time periods. Given the immediacy of socioeconomic effects of wildland fire and the emphasis on reducing greenhouse gas emissions to meet midcentury targets, the breakout group agreed that a focus on 2020-2050 would be a useful timeframe.

Federal firefighting managers are interested in a number of specific metrics at each stage of analysis of future wildfire risk, beginning with metrics on global and regional drivers, to local influences, to direct impacts, and finally metrics around responses to the impacts. These impacts in turn have feedbacks to the overarching drivers of increased wildfire risk. The set of metrics identified by the group are:

Input metrics:

a. Climate change metrics: temperature, precipitation, variability, extreme heat, dry spells, etc.
b. Wildfire model metrics: fire danger indices linked to daily weather surface patterns related to ignitability, spread rate, control difficulty, and live and dead fuels.
c. Socioeconomic metrics: population change, economic growth.

Intermediate outcome metrics:

a. Forest/range ecosystem metrics: extent and productivity of natural ecosystems.
b. Fire metrics: acres burned, PM2.5 emissions, black carbon, ozone, and other air pollution concentrations.
c. Wildfire risk metrics: probability of burning and values at risk.
d. Socioeconomic metrics: land use change/development pattern.

Impact metrics:

a. Health impacts: premature mortality, myocardial infarction, acute exacerbation of respiratory illness, mental stress.
b. Economic impacts: business disruption, infrastructure damage, houses lost.
c. Other impacts: e.g., availability of potable water.

Decision metrics

a. Priority areas for reducing fire risk (e.g., fuel treatment).
b. Evacuation route options related to potential development patterns.
c. Local zoning and ordinances to reduce risk to homeowners and other infrastructure.

Drivers

The breakout group chairs posited that there are seven major drivers of increased wildfire risk, as follows:

1. Climate change: changing forest and range ecosystems and their susceptibility to fire; changing ecosystem capacity to provide ecosystem services.
2. Human development patterns: changing fire risk as more development occurs within former wildland areas; changing demands for ecosystem services.
3. Forest and range management actions (private and public lands).
4. Fire management policies: suppression versus fuels management.
5. Adaptive capacity to respond to wildfire: community preparedness plans, emergency response plans, water provider preparedness and response strategies, land and fire management plans; land use/zoning policies that influence ability to develop into high-wildfire-risk areas.
6. Local housing policies that affect housing risk (e.g., HOA requirements for roof types, landscape maintenance.
7. Moral hazard: defining the responsibilities and risk shift between private and public sectors (e.g., houses built in high-risk areas are protected at public expense).

Modeling framework and capabilities

Wildfire risk could be examined under different assumptions about land use/exurban development, climate effects on forest and range ecosystems, and fire management options. Different risk outcomes would be associated with a different array of human health and welfare and ecosystem service impacts. In developing a modeling framework concept, the breakout group started from the perspective of what the user, a Federal firefighting manager, cares most about—risk of wildfire occurrence and extent, impacts on ecosystems, impacts on humans and infrastructure, carbon sequestration—and brainstormed the links that feed into these metrics of interest. They identified models of the drivers: regional climate models that project both means and extremes, models or other analytical tools that relate to natural ecosystems (fuels, typography, pests, and diseases), and projections of coevolving socioeconomic conditions such as changes in population, regional economics, land use and land cover, and development and expansion of the wildland-urban interface. These three systems have ecosystem and societal implications and are linked themselves directly or indirectly. The extent or severity of wildfire also depends on what the group referred to as “management levers” (e.g., forest and fire management). Similarly, the impacts of wildfire, both on people and infrastructure, are influenced by “social/policy levers” (e.g., insurance and zoning), which can lessen the severity/extent of impacts from wildfire risk. This modeling framework concept is depicted in Figure B-7. The drivers and levers also interact with air quality, human health, water quality, and flooding/landslides that are also variables of interest to the users. However, the modeling framework proposes to look at these exogenously.

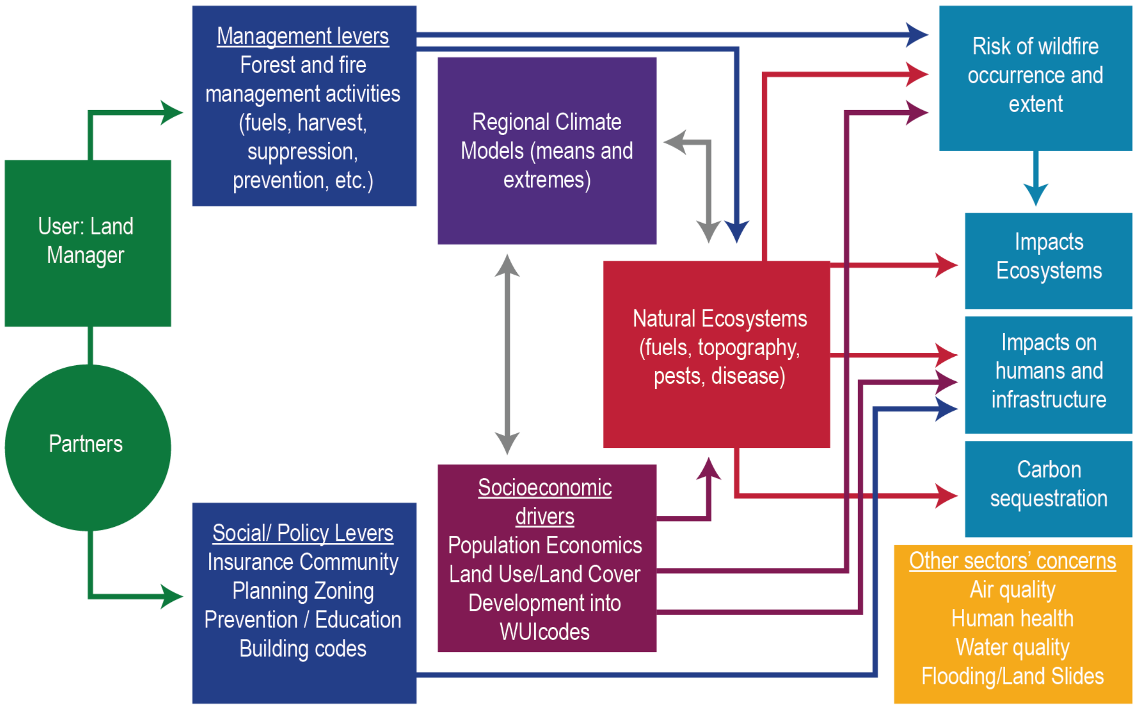

Figure B-7. Modeling framework concept for addressing wildfire impacts and management under changing climate, environmental, demographic, and policy futures.

To address these questions, the group proposed that capabilities are needed to model:

1. Future climate drivers
2. Economic or market change
3. Population characteristics, distribution, urbanization
4. Land use or cover change, wildland-urban interface
5. Forest and vegetation, including disturbances
6. Biogeochemistry
7. Human behavior and response to forest fires.

There is significant capacity for individual items on the list of needed capabilities. EPA's Integrated Climate and Land-Use Scenarios modeling system provides county-level estimates of population change and developed land characteristics. The National Center for Atmospheric Research also has capacity to project population distribution. Several models are available that project land use or land cover, housing development, and other human attributes affecting natural environments. Models also exist that incorporate climate-change drivers in forest and other natural ecosystems, with varying ability to explicitly incorporate the effects of natural and human disturbances. Fire research has produced a suite of both ecological models to project fire behavior and risk (e.g., BEHAVE, FARSITE) and decision-support models used to make fire suppression decisions in real time.[12] There has been less attention to coupling these modeling systems for assessing the long-term consequences of wildland fire risk and impacts. Current decision-support models generally focus on the short-term horizon of suppression strategies; fuel treatment models often look forward a few decades, and may not incorporate climate effects on the landscape and/or the effects of human development. Therefore, substantial opportunities exist to explore longer-term interactions between human and natural systems in relation to the risks and impacts of wildland fire.

B.3.4 Surface-water quality and ecosystem services affected by droughts, floods, and changing land use/land cover trends, Co-leads: A. Grambsch (EPA) and I. Kraucunas (PNNL)

Problem framing

Water pollution control has been a top environmental priority for decades, and the focus of significant regulation and public and private spending. Despite improvements in drinking water and water for recreational uses, harms to aquatic ecosystems and degradation of ecosystem services is highly problematic, especially that of nonpoint nutrient pollution from agriculture. EPA assessments indicate that 46% of our nation's rivers and streams are in poor biological condition, and 62% of coastal and Great Lakes nearshore waters are in fair or poor condition. State and Federal water-quality authorities continue to struggle to find efficient and effective ways to control nonpoint pollution. In addition, the recent water crisis in Flint, Michigan and the Gold King mine waste water spill in Colorado reflect the need for continued attention on point source pollution. Continued population growth and associated changes will put further pressure on aquatic ecosystems and associated ecosystem services. Managers need to understand the risks, the options for addressing them, and the merits of the alternatives. Against this backdrop, the breakout group presented the following question:

> *What combinations of adaptation measures (e.g., allocation under total maximum daily loads, watershed implementation plans, institutional/regulator design, etc.) have the greatest promise for protecting aquatic ecosystems and associated ecosystem services in different regions from evolving vulnerability resulting from population growth, land use change, and climate change?*

User perspective and needs

The breakout group approached the question through the lens of state and Federal water-quality managers who develop and implement plans to manage multiple variables (water temperatures, stream flows, water chemistry) influencing the condition of aquatic ecosystems and the ecosystem services they produce. In the simplest cases, the concern is with a small lake under the authority of a single water-quality authority that is affected by a few point sources (e.g. publicly owned treatment works or POTWs) or land-based sources (e.g., agriculture runoff from a single farm). Complex cases, such as the Chesapeake Bay, include large watersheds with river systems draining into an estuary or coastal water affected by many diverse sources of pollutants and hydrological changes (e.g., dams or diversions) at various scales with management under the purview of multiple regulatory authorities (e.g., state and Federal water-quality regulators, land use planners, Federal agricultural conservation programs, reservoir operators). In either case, it is important to account for the many disparate factors that control water quality, which is

[12] See for example, Finney, M. A. 1998. FARSITE: Fire Area Simulator—Model development and evaluation. Res. Pap.RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

challenging to do from either an observational or modeling perspective. Moreover, high-resolution spatial and temporal analysis is typically needed in order to target locations/land uses that account for a disproportionate source of pollutants. The breakout group also highlighted the need to focus not only on changes to average conditions but also disruptive events. For example, major storm events can move large volumes of legacy pollutants into stream flows or inundate control facilities. The box below lists examples of the time and spatial scales of interest and types of extremes or disruptive events affecting aquatic ecosystems and associated ecosystem services.

Time scales of interest:

a. Water infrastructure (drinking water treatment, wastewater treatment, and storm water systems are long-lived, with design life ranging from 20 to 50 years or more;
b. Total Maximum Daily Load (TMDL) watershed restoration plans can cover years to decades, with incremental milestones;
c. Realizing efficacy of best management practices for watershed management can take years to decades;
d. Regulatory pollutant control permits and reporting typically run on 3-5 year cycles (water-quality standards and criteria, National Pollutant Discharge Elimination System (NPDES) point source discharge permits, etc.);
e. Annual and seasonal upstream reservoir operations management to control flooding and provide water supply can affect downstream water-quality conditions;
f. Seasonal increases in water-body temperatures can result in power plants obtaining 'variances' to exceed allowable permit limits;
g. Operations of drinking water systems and wastewater treatment systems are sensitive to short-term weather impacts;
h. Water quality monitoring—for both reference and non-reference conditions—seasonal data collection, annual reporting, 5-year statistical analyses, long-term monitoring;

Spatial scales:

a. TMDLs tend to be at the 12-digit Hydrologic Unit Codes or reach scale;
b. NPDES permits, while based on TMDLs and water-body water-quality standards and ambient conditions, are facility specific;
c. Watershed management scales can be larger than 12-digit Hydrologic Unit Codes;
d. Infrastructure design can be urban scale to site specific;
e. Best Management Practices design can be urban scale to site specific;

Type of extremes/disruptive events:

a. Intense precipitation (wastewater overflows, damage to infrastructure, stream bed erosion, pollutant runoff);
b. Intense drought (due to lack of rain, increased evaporation, and evapotranspiration);
c. Increased 'flashiness';
d. More variability, including intense rain following by more drought (impairments to drinking water supplies, e.g., toxic Harmful Algal Blooms);
e. Cumulative impacts and seasonal shifts (invasive species, loss of habitat, e.g., cold water fisheries, impacts to endangered species, e.g., salmon);
f. Declining groundwater supplies, due to reduced recharge and increased pumping. Declining groundwater quality due to changes in chemical properties (especially due to pumping as well as aquifer storage and recovery practices);
g. Acidification (pH) due to both nutrients and absorption of CO_2.

The breakout group distinguished between "root-cause" metrics and outcome metrics of interest to this problem. This distinction can be interpreted as modeling inputs versus modeling outputs. Major metrics for the drivers or root-cause metrics are:

(a) For nonpoint pollution:
   a. Level of agricultural activity and nutrient application;
   b. Frequency and intensity of high-runoff events from urban and agricultural areas;
   c. Urban land uses and landscape characteristics describing features that influence runoff levels and quality (e.g., percent impervious);

(b) For point source pollution: changes in industrial and municipal discharges under a range of different scenarios (e.g., different degrees of urbanization or land use changes in a specific area);

(c) NOx emission levels and weather/climate-related metrics influencing water quality, quantity, and ecosystem conditions (e.g., water temperatures and seasonal patterns, precipitation intensity, soil moisture).

Major metrics for the desired modeling outcomes are:

(a) Water-quality indicators, including dissolved oxygen, water temperature, pH, levels of nitrogen and phosphorus, E. coli, and unswimmable/unusable days;

(b) Aquatic ecosystem indicators (e.g., health and number of species; presence or risk of invasive species);

(c) Health and welfare indicators such as beach closure days, loss of recreation days, cases of gastrointestinal distress;

(d) Economic indicators such as ecosystem service values, control costs, and other social welfare costs.

Drivers

The breakout group first developed a list of both non-policy and policy-related drivers of changes in water quality:

Drivers/influences (non-policy):

- Changes in climate (e.g., air and water temperature, precipitation—especially drought/low-flow conditions punctuated with infrequent heavy rainfall events);
- Changes in population, size and location of urban areas, economic activity, technology, and human diet consumption (nutrient intensity);
- Level and composition of food, feed, biofuel demand (nutrient cycles);
- Location and structure of food, feed, biofuels production (nutrient cycle);
- Energy demand and production for NOx emissions.

Drivers/influences (policy related):

- Environmental policies influencing air pollutant emissions and discharges into water bodies;
- Food and agriculture policies (e.g., price supports, conservation reserve);
- Energy policies (influencing nutrient cycles);
- Land use policies influencing the location of residential, commercial, industrial, and agricultural activities;
- Resource management actions that influence aquatic ecosystem health, function, and structure.

Modeling framework and capabilities

To arrive at a modeling framework idea for this problem, the breakout group started with a hypothetical/generic water-quality model at the watershed level and brainstormed what processes would need to be explicitly simulated and what factors would need to be considered as either drivers or boundary conditions for simulations (Figure B-8). For example, to assess nonpoint nutrient pollution from agriculture, it is necessary to estimate (either explicitly or via a scenario from another model or analysis)future agricultural production including its response to climate as well as food demand and prices, and to be able to simulate what these changes imply in terms of nutrients running off the surface. Similarly, a migration model or scenario could provide insights into where people are going to live in the future, which may inform changes in water demands and impact water quality.

Participants stressed the need to clarify processes that required explicit simulation versus those that could be represented via scenarios, supply curves, or qualitative assessments, as well as specifying the information requirements of the decision(s) that needed to be informed. The key overarching question here is: what are the functional requirements? For example, if no strong feedback loops from water quality to regional or global climate exist, then climate could most likely be treated as an exogenous set of boundary conditions The working hypothesis proposed by the group is that the factors in green boxes in Figure B-8 had no or small feedbacks and could thus be treated as scenarios or boundary conditions (perhaps originating from observations or from another model) that do not require explicit feedbacks from the watershed-scale water-quality model. However, these “external” factors should still be consistent with the assumptions in the modeling framework, which will typically require input across many disciplines, and require that modelers collaborate closely to ensure consistency. In addition, the breakout group noted that it is important for the modeling framework to account for various resilience measures that could be adopted to manage water quality, such as a breakthrough in water treatment, lower-water management requirements or a breakthrough in desalination. Some of these measures would need to be explicitly modeled, while others could be reflected in the drivers or boundary conditions.

In regard to existing capabilities, the breakout group agreed that we fairly well understand atmospheric deposition, energy-related impacts on water quality (especially temperature), and the impacts of water management. However, we need to better understand the factors controlling agricultural runoff levels, the potential impacts of wildfires and invasive species, and in some regions the locations and amounts of legacy toxic waste. We also need models that can account for the many factors that influence water quality, including in-stream biogeochemistry, as well as simulating all relevant upstream and downstream processes in an integrated way. For instance, given certain inputs, could we project when a hypoxic zone will form and how long it will stay there? Although we have capabilities for many of the green boxes in Figure B-8, in some cases we may not fully understand the impacts of these factors on the watershed. We also need to work towards water-quality models that can consistently provide the direct metrics of water quality, including characterization of uncertainties, as well as making sure that our observational systems can assess all of the key outcome metrics relevant to a particular decision.

In respect to existing water-quality models, the group highlighted the Storm Water Management Model (SWMM), a dynamic hydrology-hydraulic water-quality simulation model that is used for single-event or long-term simulation of runoff quantity and quality, particularly in urban areas; the Chesapeake Bay Program's Watershed Model, which is an enhanced Hydrological Simulation Program-Fortran (HSPF) model used to simulate nutrient and sediment load delivery to the Chesapeake Bay; and the Soil & Water Assessment Tool (SWAT), a river-basin-scale model developed to quantify the impact of land management practices in large, complex watersheds. For water management, the Water Quality Analysis Simulation Program and Water Evaluation and Planning system are widely used to help users interpret and inform water-quality responses to natural phenomena and pollution for various pollution management decisions. For understanding agricultural processes, participants pointed to the Environmental Policy Integrated Model, which is used to analyze several crop types and their management under different weather, topographical, and soil conditions. It helps to explore the trade-offs between plant growth and yield on the one hand, and environmental impacts and sustainability on the other. It is worth noting, however, that these are just a few examples of available capabilities in this area, and considerable work is required to better understand the strengths and limitations of these various tools, as well as the potential for combining them to address more complex challenges.

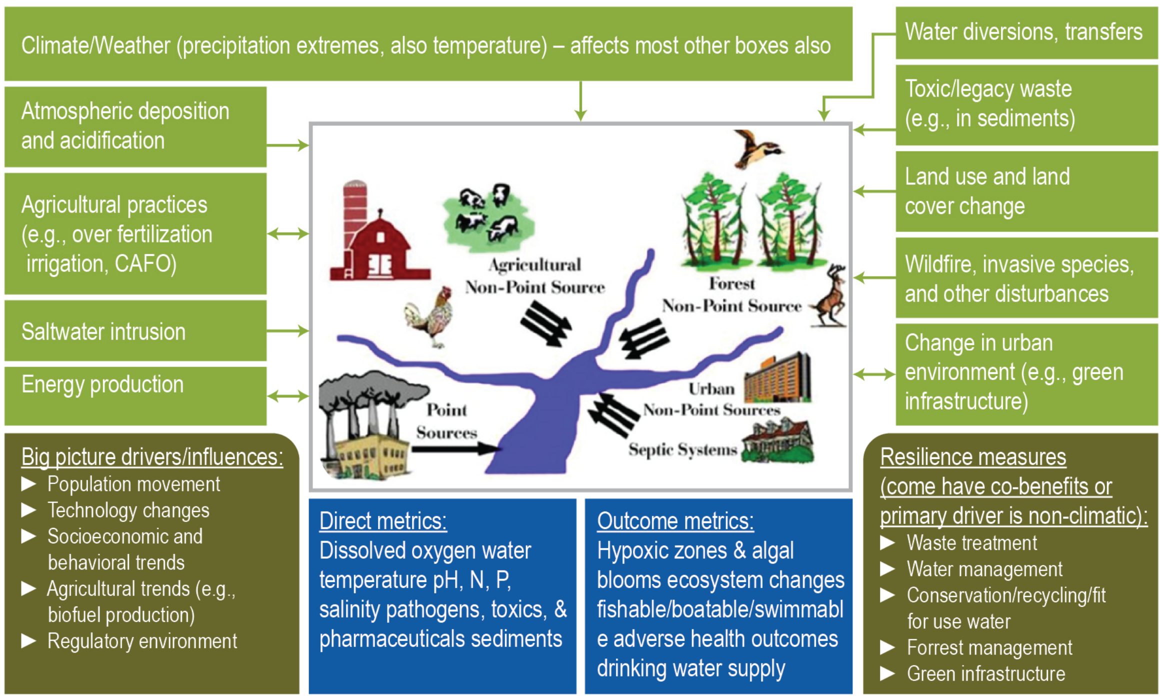

Figure B-8. Modeling framework concept for addressing surface-water quality and ecosystem services affected by droughts, floods, and changing land use/cover trends.

Appendix C – Breakout Group Questions

Example Breakout Group Questions
Topics for Discussion

Issue breakout groups (Connected and Concentrated Infrastructure and Drought across scales and sectors)

1. **Problem framing:** Short description of the Agency submitted question at the level of detail needed to plan a configuration of models to represent important drivers and feedbacks and provide output useful to answering a science question or informing a decision, including:
    a. **Objectives/user-driven desired outcomes/metrics** (metrics, a.k.a. dependent variables, decision criteria in the case of planning needs, and/or systems behavior insights in the case of research questions)
    b. **Important systems, processes, and interactions** (within spatial and temporal scales of interest but also the critical few interactions that cross scales).
    c. **Most significant decision options/uncertainties**, including siting, operational adjustments, technology insertion/substitution, demand management, redundant and heterogeneous systems, etc.
    d. **Other major sources of uncertainty** (e.g., technology innovation, and resource estimation such as groundwater affecting processes, interactions, and key outcomes)
    e. **Important constraints or external influences** (including but not limited to institutional factors)
2. **Use of the framework:** Brief description of how a modeling system (framework linking models) would be used (Who? How frequently? Requirements for uncertainty and risk characterizations? Requirements for communication of results (e.g., visualization, gaming…)? Computational environment [Desktop/ high-performance computing /…])?
3. **Conceptual diagram** of major information flows as implied by 1.a-e. (e.g., flowchart, network diagram).
4. **Description of capabilities:** Table of model components (where they exist), required information flows (where models/tools do not yet exist) and data requirements

Appendix D – Other Relevant DOE Activities

Examples of other recent DOE activities relevant to the development of an integrated modeling framework

April 20-21, 2016: USGCRP Scenarios and Interpretive Science Coordinating Group's *Multi-Scale Economic Methodologies and Scenarios Workshop* (report available at http://tinyurl.com/multi-scale-economic-methods)

- Experts from the Federal Government, the national laboratories, and academia addressed methodologies and scenarios to explore how the economic character of the United States might evolve in the future. Several participants pointed to a multi-scale approach or nested framework as one option to meet the needs of different user groups that work across many scales. Participants also explored the question of how to reconcile different sources of uncertainty in a common analytical framework, and how to constrain uncertainty as models become more complex and incorporate more feedbacks.

May 20, 2016: Accelerated Climate Modeling for Energy meeting on DOE Science Scenarios

- The half-day workshop included a brainstorming session, where science questions of interest to various participants were identified. Participants asked questions such as how might extreme weather events influence water availability and energy requirements under different scenarios, and the effect of alternative population and urbanization pathways on air quality and climate.

July 25-29, 2016: Energy Modeling Forum's *Climate Change Impacts and Integrated Assessment Workshop XXII* (Snowmass XXII Workshop), Session on Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus

- The four-day workshop brought together researchers from a variety of scientific communities to discuss coupling models from different domains, including climate science, integrated assessment, and impacts, adaptation, and vulnerability. A number of scientific challenges were addressed including that of creating a flexible framework to accommodate the different modeling needs posed by different questions.

Appendix E – Workshop Participants List

Last Name	First Name	Affiliation
Abbas	Ali	University of Southern California
Anderson	Greg	National Science Foundation
Asrar	Ghassem	Joint Global Change Research Institute, PNNL
Backhaus	Scott	Los Alamos National Laboratory
Balbus	John	National Institutes of Health
Baldwin	Sam	U.S. Department of Energy
Balk	Deborah	City University of New York
Barrett	Chris	Virginia Tech
Battey	Hoyt	U.S. Department of Energy
Bauer	Diana	U.S. Department of Energy
Bhaduri	Budhu	Oak Ridge National Laboratory
Bliss	Nadya	Arizona State University
Calvin	Kate	Joint Global Change Research Institute, PNNL
Carman	Jessie	National Oceanic and Atmospheric Administration
Clarke	Leon	Joint Global Change Research Institute, PNNL
Covel	Charles	U.S. Department of Homeland Security
D'Achille	Christopher	Tulane University
DeAngelo	Ben	U.S. Global Change Research Program
Delgado	Alison	Joint Global Change Research Institute, PNNL
Ebi	Kris	University of Washington
Fisher-Vanden	Karen	Pennsylvania State University
Flatness	Andrew	U.S. Department of Energy
Geernaert	Gary	U.S. Department of Energy
Glasmeier	Amy	Massachusetts Institute of Technology
Gober	Pat	Arizona State University
Grambsch	Anne	U.S. Environmental Protection Agency
Hnilo	Jay	U.S. Department of Energy
Horsfall	Fiona	National Oceanic and Atmospheric Administration
Joseph	Renu	U.S. Department of Energy

Last Name	First Name	Affiliation
Kindle	Andrew	ICF International
Koch	Dorothy	U.S. Department of Energy
Kopp	Bob	Rutgers State University
Kraucunas	Ian	Pacific Northwest National Laboratory
Lange	Margaret	National Geospatial-Intelligence Agency
Langner	Linda	U.S. Department of Agriculture Forest Service
Lempert	Robert	RAND
Lenihan	Michael	National Geospatial-Intelligence Agency
Lesmes	David	U.S. Department of Energy
Li	Jia	U.S. Environmental Protection Agency
McFarland	Jim	U.S. Environmental Protection Agency
Moss	Richard	Joint Global Change Research Institute, PNNL
Neumann	Jim	Industrial Economics, Inc.
O'Connor	Bob	National Science Foundation
Omitaomu	Femi	Oak Ridge National Laboratory
Orr	Marilee	U.S. Department of Homeland Security
Preston	Ben	Oak Ridge National Laboratory
Reed	Pat	Cornell University
Rice	Jennie	Smarter Decisions, LLC
Rothman	Dale	University of Denver
Ruane	Alex	National Aeronautics and Space Administration
Sands	Ron	U.S. Department of Agriculture
Schlosser	Adam	Massachusetts Institute of Technology
Sleeter	Ben	United States Geological Survey
Stein	Adam	U.S. Global Change Research Program
Sue Wing	Ian	Boston University
Sussman	Fran	ICF International
Tebaldi	Claudia	National Center for Atmospheric Research
Tidwell	Vince	Sandia National Laboratories
Vallario	Bob	U.S. Department of Energy
Van Hentenryck	Pascal	University of Michigan
Weyant	John	Stanford University
White	Kate	U.S. Army Corps of Engineers