INTEGRATED HYDRO-TERRESTRIAL MODELING

Development of a National Capability

Community Coordinating Group on Integrated Hydro-Terrestrial Modeling

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Report Contributors

Interagency Steering Committee

David Lesmes (U. S. Geological Survey)
Jessica Moerman (U. S. Department of Energy)
Tom Torgersen (National Science Foundation)
Bob Vallario (U. S. Department of Energy)

Scientific Organizing Committee

Tim Scheibe (Chair, Pacific Northwest National Laboratory)
Efi Foufoula-Georgiou (Co-Chair, University of California, Irvine)
Harry Jenter (Co-Chair, U. S. Geological Survey)

Technical Steering Committee

Ron Bingner (U. S. Department of Agriculture)
Laura Condon (University of Arizona)
Brian Cosgrove (National Oceanic and Atmospheric Administration)
Carlos Del Castillo (National Aeronautics and Space Administration)
Charles Downer (U. S. Army Corps of Engineers)
John Eylander (U. S. Army Corps of Engineers)
Michael Fienen (U. S. Geological Survey)
Nels Frazier (National Oceanic and Atmospheric Administration)
David Gochis (National Center for Atmospheric Research)
Dave Goodrich (U. S. Department of Agriculture)
Judson Harvey (U. S. Geological Survey)
Joseph Hughes (U. S. Geological Survey)
David Hyndman (Michigan State University)
John Johnston (U. S. Environmental Protection Agency)
Forrest Melton (National Aeronautics and Space Administration)
Glenn Moglen (U. S. Department of Agriculture)
David Moulton (Los Alamos National Laboratory)
Laura Lautz (National Science Foundation)
Rajbir Parmar (U. S. Environmental Protection Agency)
Brenda Rashleigh (U. S. Environmental Protection Agency)
Patrick Reed (Cornell University)
Katherine Skalak (U. S. Geological Survey)
Charuleka Varadharajan (Lawrence Berkeley National Laboratory)
Roland Viger (U. S. Geological Survey)
Nathalie Voisin (Pacific Northwest National Laboratory)
Mark Wahl (U. S. Army Corps of Engineers)

Acronyms and Abbreviations

AI	artificial intelligence
API	application programming interface
ARS	Agricultural Research Service
CEAP	Conservation Effects Assessment Project
CIGLR	Cooperative Institute for Great Lakes Research
CMTB	Coastal Model Test Bed
CNCF	Cloud Native Computing Foundation
CONUS	conterminous United States
CoP	community of practice
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science
CZO	Critical Zone Observatories
DFO	Department of Fisheries and Oceans (Canada)
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DWR	Department of Water Resources (California)
DYRESM	Dynamics Reservoir Simulation Model
E3SM	Energy Exascale Earth System Model
EPA	U.S. Environmental Protection Agency
ESMF	Earth System Modeling Framework
FAIR	findable, accessible, interoperable, reusable
FEMA	Federal Emergency Management Agency
GIS	geographic information system
GMA	Groundwater Management Agency
GRACE	Gravity Recovery and Climate Experiment
HAB	harmful algal bloom
HMT	Hydrometeorology Testbed
HPC	high-performance computing
IHTM	Integrated Hydro-Terrestrial Modeling
iLAMB	International Land Model Benchmarking Project
I/O	input/output
IT	information technology
LEMA	Local Enhanced Management Area
MAR	Managed Aquifer Recharge
NAS	National Academies of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration

NASEM	National Academies of Sciences, Engineering, and Medicine
NGO	non-governmental organization
NGWOS	Next-Generation Water Observing System
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWM	National Water Model
O&M	operations and maintenance
O2R	operations to research
OGC	Open Geospatial Consortium
OMB	Office of Management and Budget
PWC	Priority Water Challenges
QA	quality assurance
QC	quality control
R2O	research to operations
R2O2R	research to operations to research
RFP	request for proposal
SGMA	Sustainable Groundwater Management Act (California)
SPoRT	Short-term Prediction Research and Transition Center
SWAQ	Subcommittee on Water Availability and Quality
UNESCO	United Nations Educational, Scientific and Cultural Organization
UQ	uncertainty quantification
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
W3C	World Wide Web Consortium
WBD	Watershed Boundary Dataset
WQ	water quality

Executive Summary

Water is one of our most important natural resources and is essential to our national economy and security. Multiple federal government agencies have mission elements that address national needs related to water. Each water-related agency champions a unique science and/or operational mission focused on advancing a portion of the nation's ability to meet our water-related challenges, often in close collaboration with scientists from the academic community. These diverse mission needs have engendered a rich and extensive base of water-related data and modeling capabilities. While useful for their intended purposes, these capabilities are not well integrated to address complex regional problems and overarching national problems. These major investments by several federal agencies and their scientific partners, however, lay the foundation for an integrated hydro-terrestrial modeling and data infrastructure that will enhance knowledge, understanding, prediction, and management of the nation's diverse water challenges.

Creating a seamless national hydro-terrestrial modeling and data capability presents an enormous opportunity to advance operations and research leading to more effective water management. Advances are necessary not only in operational tools for forecasting but also in research to identify and resolve knowledge and data gaps that lead to uncertainties in forecast outcomes that are so large that decisions cannot be made based on those forecasts. As such, close coordination across scientific, operational, and resource management communities is required.

To this end, an interagency workshop on "Integrated Hydro-Terrestrial Modeling: Development of a National Capability" was held at the National Science Foundation (NSF) headquarters in Alexandria, Virginia in September 2019, led jointly by the NSF, the U.S. Department of Energy (DOE), and the U.S. Geological Survey (USGS), with broader interagency support provided through an interagency steering committee. This workshop provided a venue to bring together representatives of water-related agencies and their scientific partners (including university researchers) to initiate and refine a vision for national Integrated Hydro-Terrestrial Modeling (IHTM) and data infrastructure and to advance ideas that would promote that vision's development. The workshop was designed to address three critical foci to advance the development of a national IHTM capability:

1. "Priority Water Challenges" around which to motivate and initiate development;
2. Technical and methodological obstacles related to data and modeling; and
3. Organizational, structural, and cultural barriers that heretofore have impeded integration of capabilities across the federal and research landscapes.

The following "Priority Water Challenge" domain areas represent targets for initiating development of IHTM and were identified and selected in alignment with priorities of the Administration's Water Sub-Cabinet: (1) Nutrient loading, hypoxia, and harmful algal blooms; (2) Water availability in the western United States; and (3) Extreme weather-related water hazards. These water challenges span agency mission boundaries and encompass a broad range of geographies, complex system dynamics and feedbacks, and critical processes spanning hydrological, climatic, and biophysical systems as well as land-use/land-cover, agricultural, built infrastructure, and societal, economic, and decisional environments. These three Priority Water Challenges cannot be fully addressed without leveraging complementary and synergistic capabilities across multiple agencies and academia.

The water management challenges identified above mandate the development of powerful capabilities to predict and manage water availability and quality and to forecast and mitigate water-related hazards. There was broad agreement that society and the science required for future water management will need a higher-level, more integrated, and more complex modeling framework than is currently in use. Workshop participants considered research and capability needs with respect to both short-term predictions and long-term projections. Short-term predictions were discussed within the context of providing forecasts and warnings to enable emergency response and protect public health (analogous to current weather predictions that are critical to public health and the economy), and long-term projections within the context of supporting environmental management decisions that promote sustainable resource development, use, and conservation. At the same time, understanding how the hydro-terrestrial system with its strong memory and coupling to the atmosphere might dampen or enhance regional precipitation predictability at sub-seasonal to seasonal time scales is an important challenge that the IHTM framework can advance.

To further motivate and direct development of a national IHTM capability, workshop participants identified exemplary integrated use cases within the three Priority Water Challenges that cannot be fully addressed without leveraging complementary and synergistic capabilities across the scientific community. These included (a) hypoxia and harmful algal blooms in western Lake Erie; (b) hypoxia in the northern Gulf of Mexico; (c) water availability in California and the Colorado River Basin; (d) drought in California; (e) depletion of the Ogallala/High Plains aquifer; (f) complex flooding; and (g) watershed-river-reservoir-groundwater systems management.

The workshop also provided an opportunity for scientists from multiple agencies and academia to share and document the organizational, cultural, financial, and technical obstacles that must be overcome to achieve a new IHTM capability. The following technical challenges and opportunities for enhanced integration of capabilities were discussed at length:

1. Standardization of data and models to allow interoperability and reuse;
2. Development of shared testbed problems to evaluate existing and new code;
3. Development and sharing of data-model integration workflows to increase the efficiency of hydro-terrestrial modeling across scales and agencies.

Key organizational and cultural challenges discussed included how to best align different missions of water-related agencies to address common problems:

1. How to minimize duplication of effort within and across agencies;
2. How to develop reward systems that acknowledge the value of data, information, and code sharing;
3. Development of a culture of interagency cooperation and open science;
4. How to appropriately leverage and collaborate with academic scientists;
5. How to share resources across agencies and leverage existing activities to meet common objectives;
6. How to promulgate and adopt standards across agencies.

Workshop participants recognized that to build a better understanding of water across the terrestrial environment (in the national need) would require effective and efficient interagency and university collaboration, new governance approaches, and business models that overcome current organizational barriers. Although it is recognized that multiple agencies share water responsibilities, their distinct business and funding practices and current alignments may not fully support adequate solutions to complex shared problems such as the Priority Water Challenges.

Workshop participants envisioned a future in which agencies are better aligned and creatively work through effective business and funding practices, thereby enabling IHTM collaborations and partnerships that simultaneously advance the individual missions of water-related agencies, advance scientific understanding, and meet the needs of stakeholders and the Nation. A critical initial step identified at the workshop advocated for multiple agencies to invest resources (leveraging existing research and capabilities) in pilot projects designed around integrated use cases, using flexible and collaborative approaches. Such integrated use cases would not only provide rallying points for initial development and testing of an IHTM capability and build on existing collaborations and capabilities, but would also spur new governance concepts, data standards, and model interoperability solutions required for a national IHTM capability. Such investment would engender each agency having a stake in the process and would lead to some early successes that would subsequently motivate the coordination and evolution of new business and funding practices that would align missions for optimal future impact.

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1. Introduction

1.1 National Water Challenges: Impacts on Society and the Economy

> *Water—the medium for life—shapes Earth's surface and controls where and how we live. Chemical, biological, and physical processes alter and are altered by water and its constituents. Water is the most widely used resource on Earth, its mass nearly 300 times that of the atmosphere. On this foundation, humans add engineered and social systems to control, manage, use, and alter our water environment for a variety of uses and through a variety of organizational and individual decisions. Therefore, understanding the hydrologic cycle and monitoring and predicting its vagaries are of critical importance to our societies.* (NASA Decadal Survey, National Academies of Sciences, Engineering, and Medicine 2018)

Water, one of the most important natural resources on the planet, is a key agent in a broad array of physical, chemical, and biological processes that shape life and the environment. It acts as a nearly universal solvent and transport agent for diverse constituents including dissolved materials, sediments, and micro- and macro-organisms. Water is also essential to human societies and economies. In the U.S., water withdrawals and use are heavily concentrated in major economic sectors such as agriculture, energy production, and public water supply; these sectors support other economic activities such that the national (and global) economy, directly or indirectly, depends on a reliable water supply (EPA 2013).

The quantity, quality, and spatial-temporal distribution of this precious resource face many challenges related broadly to increasing human water demand, the changing nature of the hydrologic cycle, and superimposed environmental changes. Human water withdrawals globally exceed 4000 km^3, and demand has grown by approximately 1% per year since 1980 (UNESCO 2019). These demands are not spatially or temporally distributed in the same manner as water supplies (because, for example, population centers and agriculture continue to expand in arid regions), requiring significant infrastructure and energy to move and store water. Environmental perturbations such as droughts can exacerbate these disparities leading to water shortages, while extreme precipitation events can lead to dramatic floods (e.g., Hurricane Harvey, which caused $125 billion in economic losses in 2017 [https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf]) such that too much water can be as problematic as too little.

The Water Subcabinet, an informal group at the Assistant Secretary/Under Secretary level representing Executive Branch agencies with water interests, has identified three Priority Water Challenges that currently pose serious threats to individuals, society, and the national economy:

1. Nutrient loading in the Mississippi Basin and hypoxia in the Gulf of Mexico and the Great Lakes, including related sediment and contaminant transport;
2. Water availability in the west, including groundwater depletion in the Southern Ogallala aquifer and changes to water supply driven by changes in precipitation patterns and mountain snowpack; and
3. Flooding, inundation, debris flow, and other water-related hazards during extreme events, including vulnerability of contaminated sites (e.g., Superfund sites) to flooding.

Examples of other critical national water issues include the impacts of drought, effects of wildfires on water quality and availability, agricultural management, and emerging water contaminants such as microplastics.

The sustainable management of water resources in the face of these issues and accelerating changes in land use, water demand, and climate is crucial for ensuring public health (Seid-Green 2016) and securing the supply and allocation of water and food production to support human well-being and national security, while sustaining healthy ecosystems. This represents a major challenge for the 21st century (Cosgrove and Loucks 2015, Poff et al. 2016), and it is increasingly important to incorporate the human dimensions of freshwater use to understand and predict the availability and quality of freshwater resources (Konar et al. 2016).

1.2 Integrated Hydro-Terrestrial Modeling (IHTM)

A critical element of effective water management at all levels (local to national to global) is the understanding of the likely outcomes of alternative management strategies, particularly under the pressures caused by future environmental and human changes. The management challenges identified above mandate the development of powerful capabilities to predict and manage water availability and quality, and to forecast and mitigate water-related hazards. Such prediction capabilities are needed for two primary purposes:

1. Short-term predictions to provide forecasts and warnings to enable emergency response and protect public health (analogous to current weather predictions that are critical to public health and the economy); and
2. Long-term predictions to support environmental management decisions that will promote sustainable resource development, use, and conservation.

Advancing such capabilities requires not only advances in operational tools for forecasting, but also research to identify and resolve knowledge and data gaps that lead to uncertainties in forecast outcomes that are so large that decisions cannot be made based on those forecasts. This close relationship between research and operations, focused around a predictive capability to inform water management, is sometimes called the “research to operations (R2O) pipeline.” It is also important to recognize the role of operations in informing research needs, thus motivating the concept of the “research to operations to research (R2O2R) pipeline” for effective water management (e.g., National Research Council 2000, 2010). This coordination between scientific research, operational prediction, and resource management can provide the basis to solve societal problems based on actionable intelligence through continuous advancement of scientific understanding. It also emphasizes that the requisite prediction capabilities must be flexible to accommodate advances in scientific understanding and technology. Such flexibility will also position IHTM to facilitate effective responses to currently unforeseen future challenges as well as those of today.

The sustainable and efficient development, operation, and maintenance of a national water prediction/projection capability requires interagency coordination, effective use of resources (e.g., funding, expertise, data, computation), and a strategy for supporting and incorporating advances from fundamental research. Each of the participant agencies in this workshop is responsible for a unique scientific research and/or operational mission that advances the Nation’s ability to address water-related problems. However, the research and operational challenges (introduced above as the Priority Water Challenges) often span the missions of multiple agencies, and thus their solutions require the research, resources, and expertise of several agencies and academia.

The National Science Foundation (NSF) and its academic constituency have a unique role in this context: NSF invests significant resources in water-related sciences, and the resulting discoveries and scientific advances are foundational to the success of a future IHTM capability. A new study by the National Academies[1] is aimed at the development of a vision for a systems approach to studying the Earth (including water-related and human components of the Earth system), including advice on how NSF can enable this vision, and is well aligned with the concepts of IHTM developed here. Attention has been given here to active engagement of the academic community in IHTM development, and how the resulting capability could be used to advance discovery science as well as to solve specific water problems.

This workshop brought together representatives of multiple agencies with water-related mission elements, and representatives of the academic science community, to develop the initial vision for an Integrated Hydro-Terrestrial Modeling (IHTM) capability that would meet the needs outlined in the preceding paragraphs through interagency coordination and strategic links between government and academia. By combining the expertise, capabilities, and data of multiple research organizations, a robust IHTM platform would be able to represent the complex system dynamics and feedbacks that result from interactions within the terrestrial environment that includes not only the hydrological, climatic, and biophysical systems but also the land-use/land-cover, agricultural, built infrastructure, and societal, economic, and decisional environments for both operations and scenario-building understanding. This IHTM will thus support the various operational needs of the water mission agencies (within known bounds of predictability), enable solution of water-related problems at local-to-national scales, and accelerate basic science in service of the Nation. Finally, an IHTM capability will provide a research platform to enable diverse communities of academic and mission agency scientists to more efficiently engage with and leverage both research and public/private operations.

1.3 The Foundation for an IHTM Capability Exists Today

The foundation for an IHTM has already been laid through major investments by multiple individual agencies, each with its own water-related operational and/or research mission spaces. Each of the agencies participating in this workshop has capabilities that could contribute toward an IHTM framework, and each agency actively collaborates across agency boundaries to develop components in support of joint goals.

Examples of advanced hydro-terrestrial simulation capabilities include the National Water Model (NWM) being developed by the National Oceanic and Atmospheric Administration (NOAA), the National Center for Atmospheric Research, and the USGS (Cohen et al. 2018), which represents an important step towards building a robust national prediction and scenario-building capability for IHTM. The USGS also has developed national-scale water prediction capabilities such as the National Hydrology Model (Regan et al. 2018). The DOE has developed land-surface modeling capabilities with national

[1] https://www.nationalacademies.org/our-work/advancing-a-systems-approach-to-studying-the-earth-a-strategy-for-the-national-science-foundation

extent such as the Energy Exascale Earth System Model (E3SM) Land Model (Bisht et al. 2018, Tang and Riley 2018) and the Advanced Terrestrial Simulator (Painter et al. 2016) as well as integrated surface-subsurface hydrologic models at the continental scale based on the ParFLOW code (Maxwell et al. 2015). The U.S. Army Corps of Engineers (USACE) has developed and maintains a large suite of relevant software tools including HEC-HMS[2] and HEC-WAT,[3] and several of these have been packaged into the Watershed Modeling System software in collaboration with academia and industry. The U.S. Department of Agriculture (USDA) Agricultural Research Service has a large suite of software tools[4], many of which address hydrologic and water quality problems. Additionally, the NSF (with USDA partners) has invested considerably in academic research programs covering "Water Sustainability and Climate" (http://www.nsf.gov/pubs/2013/nsf13535/nsf13535.htm and previous versions) and "Innovations at the Nexus of Food, Energy and Water" (https://www.nsf.gov/pubs/2018/nsf18545/nsf18545.htm and previous versions) that have better defined and identified coupled processes and feedbacks that have expanded our understanding of these complex systems. The academic community has contributed to each of these existing capabilities through, e.g., development of fundamental theories, process understanding, algorithms, and methods for parameter estimation, as well as through direct contributions to the underlying code platforms.

Similarly, coordinated efforts by multiple agencies have resulted in widely available data sets with extensive spatial coverage, advanced through several federal initiatives. In 2002, the Office of Management and Budget (OMB) published Circular A-16, which provided "*direction for federal agencies that produce, maintain, or use spatial data either directly or indirectly in the fulfillment of their mission and provides for improvements in the coordination and use of spatial data*." Further coordination was spurred by the U.S. Office of Science and Technology Policy (Subcommittee on Water Availability and Quality or SWAQ) through the Open Water Data Initiative started in 2014 (Bales 2016, Maidment 2016). These coordinated efforts over the past two decades have led to critical data products such as the National Hydrography Dataset (NHD), the Watershed Boundary Dataset (WBD), and NHDPlus (an enhanced version of NHD). The USGS recently published a national hydrogeologic database (Clark et al. 2017). Fatichi et al. (2016) describe several other sources of spatial data sets including soil survey, precipitation, meteorological forcing, and river morphology, many of which have been provided by federal agencies. The U.S. Environmental Protection Agency (EPA) internet site on "Water Data and Tools[5]" provides access to an extensive set of EPA and interagency software and data sets. Remotely sensed data such as those provided by the National Aeronautics and Space Administration (NASA)'s Earth Observing System further expand data types to include precipitation, vegetation and land use/land cover, soil moisture, changes in groundwater levels, and many others (NAS 2018a). The NSF has sponsored the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI[6]), which has developed an extensive toolset for water-related data access, analysis and collaboration, including data from federal agencies as well as academic institutions. Work is ongoing not only to increase data availability, but also to break down barriers to effective use of these data in model development, e.g., HydroShare (Horsburgh et al. 2016).

[2] https://www.hec.usace.army.mil/FactSheets/Software/HEC_FactSheet_HEC-HMS.pdf
[3] https://www.hec.usace.army.mil/FactSheets/Software/HEC_FactSheet_HEC-WAT.pdf
[4] https://www.ars.usda.gov/research/software/
[5] https://www.epa.gov/waterdata
[6] https://www.cuahsi.org/

Recent developments offer the opportunity to build on these existing capabilities and collaborations to advance an unprecedented national capability for solution of critical water problems. For example, significant new data acquisition initiatives (e.g., the NASA Ecostress mission[7] and the USGS Next-Generation Water Observing System [NGWOS[8]]) will provide hydrologic information of unprecedented quality and scale. DOE is developing and operating world-class, high-performance computational facilities that are enabling hydro-terrestrial simulations with unprecedented process fidelity and spatial/temporal resolution (Bland et al. 2017), as well as investing in artificial intelligence (AI)-enabled, next-generation watershed simulation software through the ExaSheds project[9]. NSF is establishing a new Critical Zone Collaborative Network[10], building on the past successes of the Critical Zone Observatories (CZOs); these and similar observatory systems significantly advance collaboration and multidisciplinary research that consider hydrologic problems in broader contexts (Gran et al. 2019). Importantly, these developments are occurring within the context of ever-increasing open science and collaboration (NAS 2018b, U.S. DOE 2019) that will further empower interagency cooperation to address national Priority Water Challenges.

The list of examples above is far from exhaustive, and all the participating agencies have many other resources and capabilities not listed here that can support IHTM. Increasing the level of coordination, sharing, and collaboration can build on this foundation to benefit each agency's mission individually, and to serve science and society broadly.

1.4 A Notional Look Ahead

Although the development of a powerful new IHTM capability is currently within our reach, we recognize that significant organizational, cultural, financial, and technical obstacles must be overcome to achieve this vision. This workshop provided an opportunity for scientists from multiple agencies and academia to share and document these challenges, and to identify potential approaches and tangible next steps to address them.

Organizational challenges include how to best align different missions of water-related agencies to address common problems, how to minimize duplication of effort within and across agencies, and how to best engage academia in advancing the science base of IHTM. Cultural issues include developing reward systems that acknowledge the value of data, information, and code sharing, and developing a culture of interagency cooperation and open science. Financial issues include how to share resources across agencies and leverage existing activities to meet common objectives. Technical issues include standardization of data and models to allow interoperability and reuse, development of shared testbed problems to evaluate existing and new code, development and sharing of data-model integration workflows to increase the efficiency of hydro-terrestrial modeling, and improved strategies to incorporate new research outcomes into modeling frameworks. These and other challenges are defined and discussed in greater detail in the ensuing sections.

[7] https://ecostress.jpl.nasa.gov/

[8] https://www.usgs.gov/mission-areas/water-resources/science/usgs-next-generation-water-observing-system-ngwos?qt-science_center_objects=0#qt-science_center_objects

[9] https://eesa.lbl.gov/exasheds-advancing-watershed-system-understanding-through-exascale-simulation-and-machine-learning/

[10] https://www.nsf.gov/pubs/2019/nsf19586/nsf19586.htm

A critical step toward the development of a powerful IHTM capability is full adoption by participating agencies of principles of "Open Science by Design". This concept, promoted by a recent report of the National Academies of Sciences, Engineering, and Medicine (NAS 2018b), is a set of principles and practices intentionally aimed at infusing openness into the entire research enterprise and throughout the research life cycle, with the aim of improving the quality of scientific output. The potential benefits of fully implementing open science practices across the IHTM community include better data support for decision-making, more accurate predictions and actionable products for operational and long-term management, and increased cost efficiency (Figure 1). As first steps toward these objectives, workshop participants proposed convening a multi-agency working group with liaisons to generate community buy-in, create incentives, and co-design a pilot project around data and model-sharing needed for one or more of the Priority Water Challenges. More detailed discussion of the outcomes of the workshop breakout sessions on Open Science by Design is provided in Section 7.

Figure 1. The perceived benefits of implementing open science practices across the IHTM community, presented as a word cloud derived from workshop outputs.

To support effective and efficient interagency collaboration including open data and models, we must implement new governance approaches and business models that overcome current organizational barriers. Although it is recognized that multiple agencies share water responsibilities and fund water-related research, their distinct practices and current alignments may not fully support end-to-end solution of national problems such as the Priority Water Challenges. Workshop participants envisioned a future in which agencies are better aligned and creatively working through effective business and funding practices, thereby enabling impactful IHTM collaborations and partnerships at a variety of levels that advance their individual missions, improve the predictability of forecasts and projections, and meet the needs of their stakeholders and the Nation. The success of the IHTM vision depends on participation by multiple federal agencies, with many or all the participants and the academic community highly engaged in development activities (Figure 2). High participation will enrich the capabilities of the IHTM software ecosystem and its ability to address issues that span the missions of several federal agencies.

Integrated use cases, based on the Priority Water Challenges as described in Chapter 2, will provide the rallying points for initial development and testing of an IHTM capability. These will build on existing interagency collaborations and expand to include new governance concepts, data standards, and model interoperability solutions. A critical initial step identified in the breakout sessions was advocating for multiple agencies to invest resources (leveraging existing research and capabilities) in pilot projects designed around the integrated use cases and using flexible and collaborative approaches. Such investment would engender each agency having a stake in the process and would lead to some early successes that would subsequently motivate the coordination and evolution of new business and funding practices that would align missions for optimal future impact. More detailed discussion of the outcomes of the workshop breakout sessions on Mission Alignment, Business, and Funding Practices, including an expanded roadmap, is provided in Section 8.

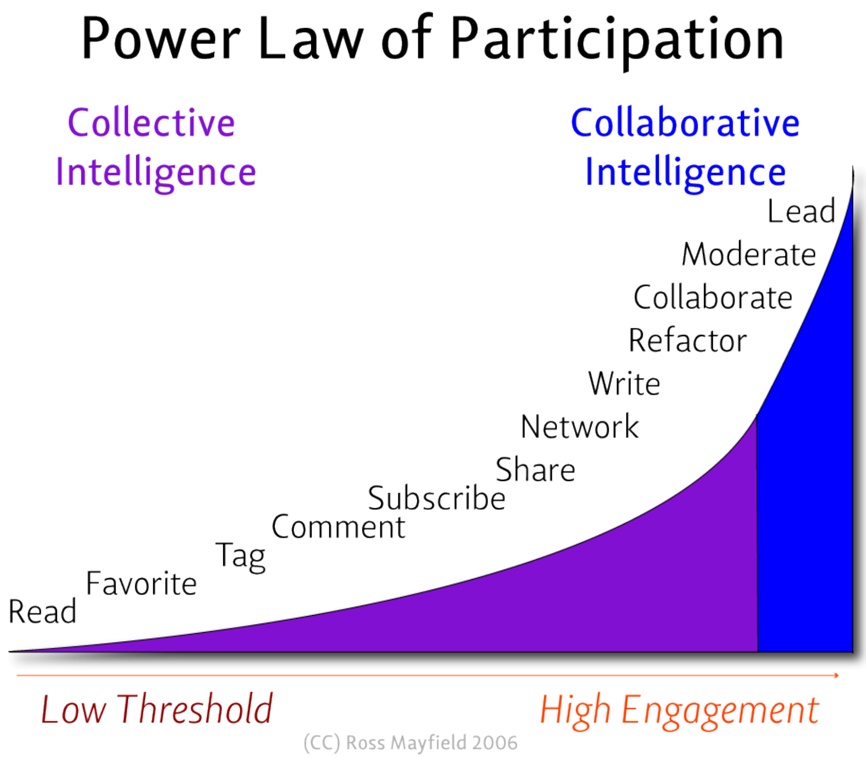

Figure 2. Interagency collaboration can bring groups together to create value for the common good. However, participation is limited by availability of time and resources, many participants may not be highly engaged, and most beneficiaries tend to be free riders upon community value. Nevertheless, even low-threshold participation amounts to collective intelligence, and strong engagement by a limited number of people provides highly impactful collaborative intelligence. Source: https://ross.typepad.com/blog/2006/04/power_law_of_pa.html

The remainder of this report provides additional information on challenges and solutions identified during the workshop, including those in several cross-cutting technical areas, and proposes more detailed action plans for implementation of an IHTM capability.

2. Priority Water Challenges Motivate an IHTM Capability

Three Priority Water Challenges motivate and comprise major use-case targets for development of IHTM. These were identified and selected by the workshop organizing committee as aligning with priorities of the Administration's Water Subcabinet: (1) Nutrient loading, hypoxia, and harmful algal blooms; (2) Water availability in the western United States; and (3) Extreme-weather-related water hazards. These water challenges span agency mission boundaries and encompass a broad range of geographies, complex system dynamics and feedbacks, and critical processes spanning hydrological, climatic, and biophysical systems as well as land-use/land-cover, agricultural, built infrastructure, and societal, economic, and decisional environments. These three Priority Water Challenges cannot be fully addressed without leveraging complementary and synergistic capabilities across multiple agencies.

These water management challenges mandate the development of powerful capabilities to predict and manage water availability and quality and to forecast and mitigate water-related hazards. There was broad agreement that society and the science required for future water management will need a higher-level, more integrated, and more complex modeling framework than is currently in use. Workshop participants considered capability needs with respect to both short-term (< 1 year) predictions and long-term (>1 year) projections. Short-term predictions were discussed within the context of providing forecasts and warnings to enable emergency response and protect public health (analogous to current weather predictions that are critical to public health and the economy) and long-term projections to support environmental management decisions that promote sustainable resource development, use, and conservation.

2.1 Hypoxia, Excess Nutrients, and Harmful Algal Blooms

Undesirable algal blooms and hypoxia are growing hazards to water resources and society (Glibert et al. 2010, Huisman et al. 2018). Harmful algal blooms (HABs) and hypoxia are primarily a result of high nutrient loading to sensitive receiving waters, including reservoirs, lakes, estuaries and coastal areas, and certain types of rivers. Negative effects of hypoxia and HABs include direct and indirect impacts such as fish kills, human and animal irritation and toxicity, threatened drinking water supplies, reduced societal amenities including real estate values and recreation quality, and related changes in water chemistry that can further degrade water quality (Smayda 1997). An outstanding example is the shutdown of the city of Toledo, Ohio's municipal water intake for a brief period during the summer of 2014 as a result of increasing concentrations of microcystin, a toxic byproduct of the increasingly common cyanobacterial blooms in Lake Erie.

2.1.1 The Current Situation

The type, extent, and duration of harmful algal blooms, and whether or not they are accompanied by hypoxic events, depend on a myriad of interacting physical, chemical, and biological factors that are challenging to predict. The trigger for hypoxia and HABs often involves transport of high levels of nutrients in excess of typical biological needs from upstream sources in watersheds, or by release of nutrients from storage in the sediments beneath affected waters (Figure 3). Watershed sources of nutrients may include atmospheric deposition, geologic sources, distributed applications of nutrients with agricultural fertilizer, and localized sources such as animal feedlots and wastewater treatment plants.

Although high nutrient loading is considered a principal driver, other important drivers of hypoxia and HABs include changes in ratios of nutrients and other biologically important constituents such as silica and particulate organic carbon. Ratios of available elements and physical factors such as water body temperature and stratification influence the type of algae and the potential for hypoxia in the affected water body. Extreme precipitation or the timing of precipitation interacting with other events (e.g., crop fertilization) often plays a role in delivering high loads of nutrients and also may be responsible for the transport of planktonic cysts from upstream source areas such as small ponds or reservoirs.

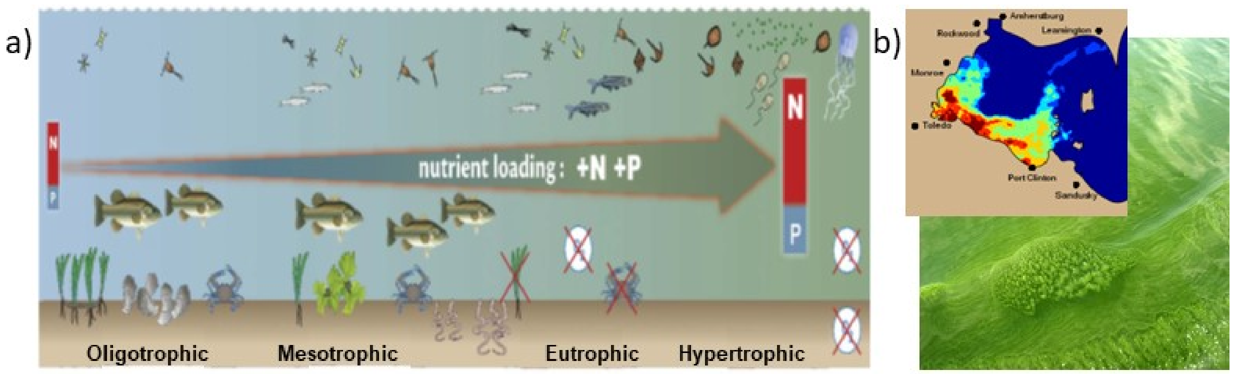

Figure 3. (a) Illustration of the impacts of excessive nutrient loading, hypoxia, and HABs on aquatic ecosystem biodiversity and function in freshwater (e.g., western Lake Erie) and marine (e.g., northern Gulf of Mexico) systems (from Glibert 2017); (b) A photograph of a lake shoreline during a cynanobacterial bloom with an inset map of a bloom distribution in western Lake Erie. Credit: NOAA Great Lakes Environmental Research Laboratory, https://www.noaa.gov/what-is-harmful-algal-bloom.

2.1.2 The Need for Integrated Forecasting

Harmful algal blooms and hypoxia problems are widespread geographically across freshwater and marine systems. Several federal agencies share lead responsibilities in addressing these problems, data are fragmented among agencies, and although there are many partnerships there is often a lack of coordination across the agencies and with academics on how to further our understanding and act more effectively to lessen the impacts. Models of agricultural and urban management practices that affect hydrologic loading of applied nutrients from watersheds often are not strongly linked to models of the resulting biological responses in receiving waters (Ganju et al. 2015, Hansen et al. 2018). For example, predictions of HABs and hypoxia in lakes and coastal systems are linked to measurements of nutrient loading by freshwater runoff, but often the approach is empirical and based in statistical relationships that lack transferability to other receiving waters (Scavia et al. 2017, Czuba et al. 2018). Despite progress in data collection and synthesis, Sobota et al. (2013) indicated the need for improved spatial and temporal quantification of agricultural nutrient management data, more monitoring of livestock and human waste management, and biological nitrogen fixation characterization in non-cultivated ecosystems.

Integrated modeling of HABs, hypoxia, and nutrient loading is a significant challenge. On the positive side, the estimation of nutrient loading from watersheds is widely practiced (e.g., Fu et al. 2019) and eutrophication models are well developed (e.g., Cerco and Noel 2013). Additionally, capabilities are advancing in using remotely sensed measurement of HABs (Schaeffer et al. 2018) and in estimates of water clarity, biological productivity, and other surrogate measurements relevant to assessing the nutrient and dissolved oxygen conditions in aquatic ecosystems (Viviano et al. 2014, Bernhardt et al. 2018, Boardman et al. 2019). However, we still lack knowledge on the relative roles of recently mobilized sources of constituents being transported with surface runoff or from slower pathways through subsurface flows. We need models that can simulate important causal factors such as the distribution and reactivity of nutrients moving through the faster and slower hydrologic components of the terrestrial system that can identify opportunities for management practices to remediate or mitigate excessive loading of nutrients and labile carbon to waterways. There is further need for integrated models that can assess the probability of the occurrence of hypoxia or HABs through integration of advanced knowledge of terrestrial loading of constituents as well as the release of "legacy" nutrients and other constituents stored internally within river, lake, and estuarine sediments.

Needs for Near-Term Forecasting

Several models currently link land use and associated nutrient runoff with hydrologic transport processes to predict downstream nutrient loading, but very few models integrate those processes with the broader suite of biological processes and responses in the receiving waters where HABs and hypoxia become a problem. Improving near-term forecasts for HABs and hypoxia events could focus on expanding sensor-based networks of measurements linking the source areas to the impacted water bodies. In specific areas with a history of problems with hypoxia and HABs, there may already be well-developed predictions of the extent and severity of hypoxia or HABs for the upcoming season (e.g., Scavia et al. 2017), but the transfer value of those methods has generally been limited because of the costs involved. Early warning systems could potentially be established in more places if the setup and maintenance costs could be lowered using sensor technology and with shared knowledge on the most effective model structures (e.g., Deitz et al. 2018). Such systems could track and update near-term forecasts of water quality exceedances or levels of concern for nutrients, measurements of dissolved oxygen using emerging low-cost sensors, and more cheaply measured surrogates such as turbidity to improve probabilistic forecasts of the likelihood of hypoxia events or HABs outbreaks. At least initially, we expect less emphasis on modeling the detailed system processes and more on improving the accuracy and utility of near-term forecasts.

Needs for Long-Term Projection

Longer-term projections for changing conditions of land use or climate will require models that can represent the key biophysical processes and integrate them with changing land use and management practices all the way from headwaters through the coastal receiving waters. Current models do not adequately capture the full range of physical and biochemical processes to simulate the most important processes that determine the fate of nutrients in upland soils and groundwaters, ponds, wetlands, riparian zones and floodplains, riverine sediments, and in reservoirs, lakes, and estuaries. Integrated models also must be able to represent influences of hydrologic alteration by natural and societal drivers as well as changing land cover and anthropogenic sources of constituents, and specific conservation practices on transport and reaction. Only recently has significant progress been made in linking the local effects of specific processes to large-scale cumulative effects in nutrient loading (e.g., Gomez-Velez et al. 2015, Czuba et al. 2018) in ways that can specify the effectiveness of specific conservation practices (e.g., Garcia et al. 2016). In the long term, these models should also consider the externalities of human behavior such as policy, market choice, and producer decisions that in the past have generally not been included.

2.1.3 Exemplary Use Cases Demonstrating Progress and Potential

The two most publicly acknowledged and focused problems in hypoxia and HAB outbreaks are in Lake Erie and the Gulf of Mexico. Lake Erie HAB outbreaks are generally thought to be the result of the timing of agricultural fertilization with respect to river flow and timing/strength of lake stratification. As farmers fertilize for crops in the spring, heavier springtime rains can wash off the applied fertilizer (possibly causing farmers to re-fertilize), which then accumulates in a stratified Lake Erie. This nutrient input causes algal blooms that harm water quality and impact recreation and municipal water intake. Stimulation of toxic algal blooms is common, leading to much wider water quality problems. In the Gulf of Mexico, nutrient applications across the Mississippi River drainage system are delivered to the Gulf and stimulate algal blooms. These blooms settle to the ocean (or lake) bottom, consume oxygen, and stimulate hypoxia that is influenced by many oceanic/lacustrine mixing processes.

HABS and Hypoxia in Western Lake Erie

In the 1970s, Lake Erie experienced significant hypoxia as a result of phosphorus loading from detergents and urban wastewater disposal. Upgrading of wastewater treatment plants enabled the lake to mostly recover. However, Lake Erie is now undergoing the effects again as nutrient loading (phosphorus and nitrogen) from now predominantly agricultural watersheds surrounding western Lake Erie fuels cyanobacteria blooms and hypoxia in the lake (Scavia et al. 2014). Up to 3,000 square miles of Lake Erie experience hypoxia between July and October, with the size and severity of problems being influenced by lake temperature, hydrodynamics, and changing patterns of precipitation quantity, timing, intensity, and loading of nutrients and labile carbon from the watershed to the lake. Economic and societal impacts include risks to public water systems such as shutdowns of municipal water intakes because of unacceptable concentrations of the toxin microcystin, and related effects of toxicity such as shutdowns of recreational beaches. Lake Erie HABs have the potential to affect water supplies of 11 million people (Lee et al. 2015). Also, hypoxic water can be corrosive to service pipes when it enters drinking water intakes and can create health risks associated with elevated levels of manganese; in the lake itself it can cause contamination with metals released by sediments; reduced summer habitat for recreational and commercial fisheries; and diminished effectiveness of efforts to control eutrophication due to internal loading of phosphorus from hypoxic sediments (Steffensen 2008).

Integrated hydro-terrestrial modeling (IHTM) can improve accounting of agricultural and urban nutrient inputs to the lake, transport of nutrients and biological production within the lake, and, ultimately, the targets for reducing nutrient loading as a means to control hypoxia (Manning et al. 2019). Scientific and technical challenges for IHTM development include collecting sufficient land cover, water flow, nutrient, and ancillary physicochemical data to permit the prediction of nutrient loading from small and mid-sized watersheds and their tributaries to the lake, as well as validating a predictive understanding of the controls on HABs' intensity, transport, and toxicity. Modeling limitations must be overcome as well, including building parsimonious models that can be efficiently transferred to other basins or scaled across large regions that sufficiently represent the processes.

IHTM capability would provide the scientific benefit of improved targets for nutrient loading reductions and conservation practices to reduce hypoxia and HABs, as well as serving the societal benefits of drinking water security, productive and sustainable fisheries, and improved recreational and aesthetic value.

Potential developers of IHTM capabilities include NOAA, the Cooperative Institute for Great Lakes Research (CIGLR), and USGS; these agencies, plus the Department of Fisheries and Oceans Canada (DFO), state environmental agencies, and academic researchers are potential users of IHTM capabilities. Primary stakeholders include public water utilities, recreational and charter anglers, other recreational users of Lake Erie, and coastal communities in Ohio and Michigan. A key milestone for near-term (0−2 years) IHTM development could be the loose coupling of models (e.g., watershed, groundwater, and river models coupled to lake models); a mid-term (2−5 years) milestone could develop a more tightly coupled framework; and the long-term (5−10 years) goal is an operational product that interacts with seasonal early warning systems by predicting river discharge, nutrient loads, HAB risk, and hypoxic extent and duration.

Hypoxia in the Northern Gulf of Mexico

Nutrient loading to Mississippi River tributaries and transport to the Gulf of Mexico is a primary contributor to a large hypoxic zone that develops annually in the northern Gulf of Mexico (Bianchi et al. 2010). A unique partnership known as the Mississippi River/Gulf of Mexico Hypoxia Task Force is addressing the problem through focused representation of federal agencies, environmental agencies of 12 states, and associated local governments and non-governmental organizations (NGOs). The Task Force’s broad set of representatives have targeted specific objectives including 1) agreeing on a common set of methods of quantifying and evaluating progress, and 2) supporting innovative research and tools that are impactful; e.g., forecasting size or persistence of hypoxia or demonstrating the value of specific best management practices in reducing nutrient loads. Furthermore, the Task Force has encouraged modeling to improve nutrient source attribution to particular areas of the Mississippi Basin, as well as the use of the USDA Conservation Effects Assessment Project (CEAP) and other information about farm conservation practices to specify the effectiveness of specific management actions (Figure 4; also see Garcia et al. 2016), as well as improvements to spring forecasts of the likely extent and severity of hypoxia later in the year (Scavia et al. 2017).

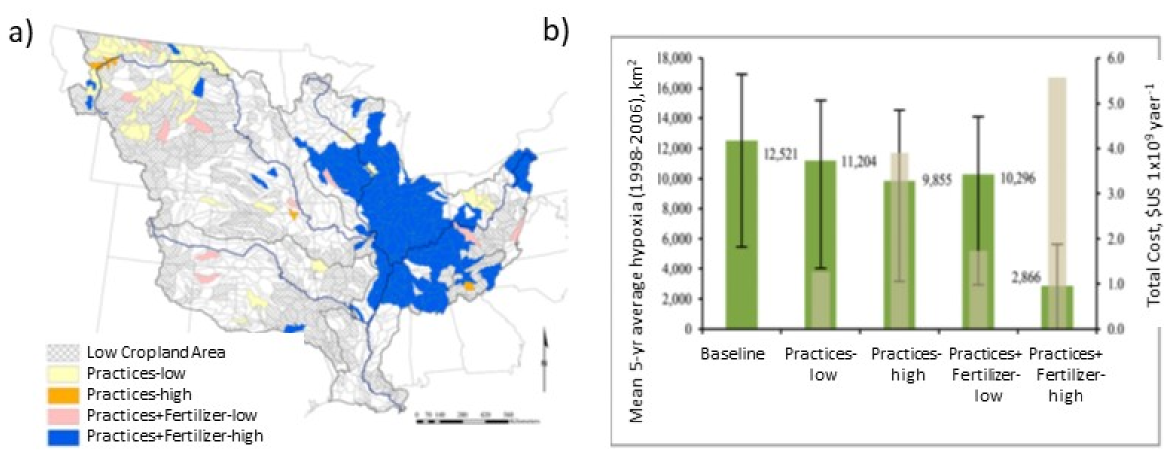

Figure 4. (a) A recent example of an integrated model of changing cropland conservation practices for the midwestern United States that was projected to achieve a 60% reduction in the mean 5-year average of hypoxia area in the northern Gulf of Mexico. (b) The present baseline and projected reductions in hypoxia area size resulting from various modeled levels of cropland conservation practices and their associated costs. Reproduced from Rabotyagov et al. 2014.

However, the processes and pathways linking river flux of nutrients to hypoxic zone formation in the Gulf of Mexico and thus the extent and duration of hypoxia remain difficult to predict based on physically based models. Seasonal forecasting of hypoxia in the northern Gulf of Mexico has been successful based on measured springtime nitrogen loading (Scavia 2017), although the empirical basis of the forecasts ensures that they are not transferable to other areas. It is clear that more advanced forecasts will require more than just accurate estimation of nutrient loading from the Mississippi River Basin (Fennel et al. 2016). More explicit modeling of the dominant processes and triggers for nutrient loading in the extensive headwaters and the role of legacy storage of nutrients and remobilization throughout the river system and estuarine transition could be beneficial, as would machine-learning approaches in data-rich areas. Improved predictions of the onset and growth of the hypoxic area in the Gulf depend on combining improved estimates of nutrient loading with loading estimates of carbon, silica, and other important constituents, and physicochemical factors such as temperature, stratification, and mixing in the transition from freshwater to estuarine to marine environments. In the future, integrated hydro-terrestrial models (IHTMs) can link watershed, river, and coastal models to help identify the dominant physical and chemical processes and the most effective strategies to reduce nutrient loading and hypoxic area based on cost-benefit analysis of scenarios. Technical barriers include the timely acquisition and harmonization of measurements acquired by multiple agencies, standardized input/output (I/O) for models at various spatial and temporal scales, and the challenges of model validation and coupling to other models.

Potential contributors to an IHTM to address this Priority Water Challenge include USGS, NOAA, USDA, EPA, and academic researchers. The models will integrate watershed drivers, riverine nutrient loading, and coastal hypoxia formation in new ways that help identify the most practical and effective management opportunities for Gulf hypoxia. Potential stakeholders and customers include 12 states, numerous regional water management agencies, local municipalities, the interagency Hypoxia Task Force, agricultural interest groups, NGOs, and others. Key milestones for near-term (0−2 years) advancements in IHTM development could include daily, seasonal, and decadal (scenario-driven) forecasts of riverine nutrient loading and improved hypoxia forecasts with components that are transferable elsewhere; mid-term (2−5 years) milestones could include a tightly coupled framework for physically and biogeochemically based model predictions; and the long-term (5−10 years) goal could include scenario-based decadal predictions integrated with operational responses to hydrologic intensification and land use changes to better manage nutrient loading and hypoxia.

2.1.4 Desired Outcomes and Impacts on Science and Society

To advance understanding of hypoxia, HABs, and nutrient loading we must advance our understanding of causation and its complexity. The path forward makes use of a new generation of models, featuring hybrid models that are physics-based but exploit the capabilities of artificial intelligence and machine learning. Advancements include bringing lake, ocean, catchment, and socio-economic factors together in a probabilistic framework that works alongside more site-specific, physically based models (Manning et al. 2019, Moe et al. 2019). The results can improve accuracy of forecasts and improve understanding of physical, chemical, and biological controls on hypoxia, HABs, and water quality in ways that are potentially applicable to other challenging non-point contaminants.

Better understanding and prediction would lead to improved management plans and guidance for agricultural practices. For example, improved predictive capabilities would enable better protection of public health through improved notification and response. Results would also be applicable to other challenging non-point contaminants. Success is built on greater focus and coordination among agencies, agency researchers, and academic scientists to leverage funding and resources. Improvements take shape in multiple dimensions of human health, better ecosystem services, and economic benefits. Key themes of "common platforms", "shared data streams", and "standardization" can make all products maximally useful across national/regional/state/local scales. Such broad participation and cooperation can revolutionize how science serves society and highlights the need for a platform to connect producers and consumers of scientific HAB information by providing universal access to data, models, tools, and methods.

The workshop participants envisioned outcomes for near-term forecasting and long-term projections. Those outcomes and their perceived benefits to science and society are summarized in the following text. For additional details, see the summary logic models produced from workshop materials (Appendix 3).

Outcomes for Near-Term Forecasting

A near-term forecasting capability would serve a need for operational forecasts of evolving surface water quality over periods of days to months. Predictive capabilities would enable better protection of public health through improved notification and response. Developing the capability to integrate near-term forecasts of largely unalterable meteorological and biological conditions with human activities may serve as the basis for a new era of operational adaptability in hydrologic control, agriculture, waste management, and other areas that currently lack the information needed to inform dynamic decision-making. Results would be in the form of timely, quantitative information relevant to water suppliers, treatment facilities, recreational water users, and others to quickly respond to changing conditions.

To be successful, integration is needed across hydrologic, biological, economic, and social models, with emphasis on decision-support tools based on delivering seven- to-ten-day forecasting of HABs with uncertainty in needed areas. The ultimate goal would be defined by an IHTM with integrated water quality models that could be adapted to predict HABs outbreaks anywhere in real time. That level of success, for many reasons, could be unrealistic for the near future, but steps toward such a model would provide a starting point to refine and improve empirically based models in high-priority areas where blooms are becoming a problem.

Outcomes for Long-Term Projection

Model hindcasting and long-term projections improve predictive understanding by identifying the causes of present-day conditions as well as project future water-quality outcomes that may result from alternative management scenarios (Norton et al. 2012). Models are needed that provide more reliable explanatory behaviors and future predictions of nutrient export from source regions, and that identify knowledge gaps early and integrate the best scientific information with socio-economic outlooks in long-term planning. Integrated models are especially needed to identify feedbacks, synchronicities, couplings, and non-linear behaviors. Increasing cooperation among agencies and coordination with academic communities will be essential to achieve the necessary concentration of resources to predict sources and variability of nutrient inputs and to develop actionable outcomes that can help stakeholders with the informed decision-making across space and time that can effectively reduce hypoxia and HABs' impacts.

The long-term goal is to develop models to produce practical products and tools for prediction everywhere. Future model projections are expected to improve management planning and direct actions by stakeholders that mitigate the occurrence and harmful effects of hypoxia and HABs by identifying "optimal" scientific and socio-economic strategies and policies for nutrient management. Useful models will emphasize decision support, multi-scale representation of processes, and coupled human-natural system models for co-evolutionary dynamics of human actions and socio-economic factors with natural system physicochemical dynamics.

Successful models should be capable of identifying the effectiveness of specific management actions, field-scale best management practices, economic incentives, and related opportunities that can help mitigate undesirable outcomes. Model outcomes should, for example, provide guidance to water resource planners charged with prioritizing best management practices that may affect water resources for decades to come. An important key to success of integrated models is the inclusion of socio-economic tradeoffs (on both the farm and watershed scale) that specify the costs and benefits of lessening the threats to human health and preserving ecosystem functions. Success will be measured based on the value of warnings and suitable mitigations that can produce an overall decrease in the risks to human health and the aquatic ecosystem functions that sustain social and economic wellbeing.

2.2 Water Availability in the Western U.S.

Water is typically more limiting to society and the environment in the western United States than in the rest of the country. As a result, there is a history of dam building and inter-basin water transfers in the west. It is now becoming clear that even with these human modifications of the western environment, water availability is still an issue with few guaranteed means to alleviate the problem. Water availability and management in the western states is thus a priority challenge.

2.2.1 The Current Situation

The western U.S. includes 17 states (Arizona, California, Colorado, Idaho, Kansas, Montana, Nevada, Nebraska, New Mexico, North Dakota, South Dakota, Oklahoma, Oregon, Texas, Utah, Washington, and Wyoming) (Figure 5a). A particularity of the region is that water is scarce and highly variable (Figure 5b), leading to complex interconnected management practices to support the multitude of water uses and comply with water laws (Kirchoff and Dilling 2016). Though water is scarce, this region is home to 35% of the U.S. population and 74% of irrigated land for crops. Additionally, human and agricultural activities in the western U.S. lead to 50% of all conterminous U.S. (CONUS) freshwater withdrawals (Dieter et al. 2018) (Figure 5c and Figure 6). Furthermore, about 70% of U.S. hydropower is generated in the western U.S., with 56% generated in California, Oregon, and Washington alone (Harris and Diehl 2019). The combination of high variability, heavy reliance on surface water supply, competing demands, and limited sector-specific flexibility to rely on both groundwater and surface water (Figure 5d and Figure 6) creates a complex coordination requirement. Water availability and management in this region needs to be understood and accurately predicted to support this complex coordination and meet competing water demands.

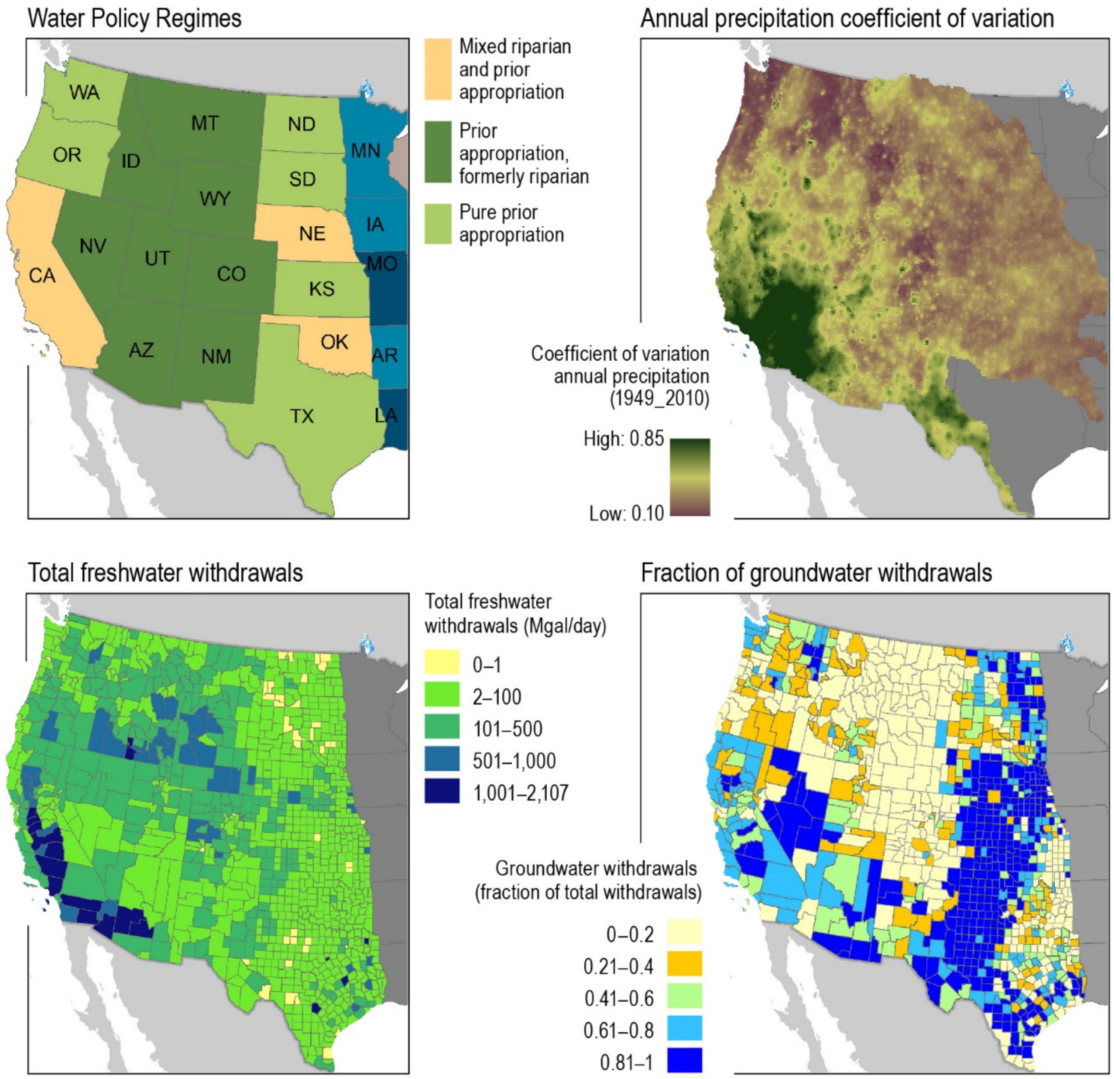

Figure 5. (a) Western states water appropriation systems that guide the allocation of water among users (Source: Gleick et al. 2011); (b) Annual precipitation coefficient of variation is the ratio of standard deviation of annual precipitation over the mean annual precipitation (Data source: Maurer et al. 2002). The coefficients highlight the variability in annual water availability and the associated challenges for seasonal planning leveraging water storage technologies where available; (c) 2015 total freshwater withdrawals per county to understand spatial variability on water dependencies (Data source: Dieter et al. 2018); and (d) Fraction of total freshwater withdrawals coming from groundwater in contrast with surface water (Data source: Dieter et al. 2018).

Groundwater allows for mitigation of annual precipitation variability but tends to be overused and depleted, putting regions at risk of further scarcity over the long term.

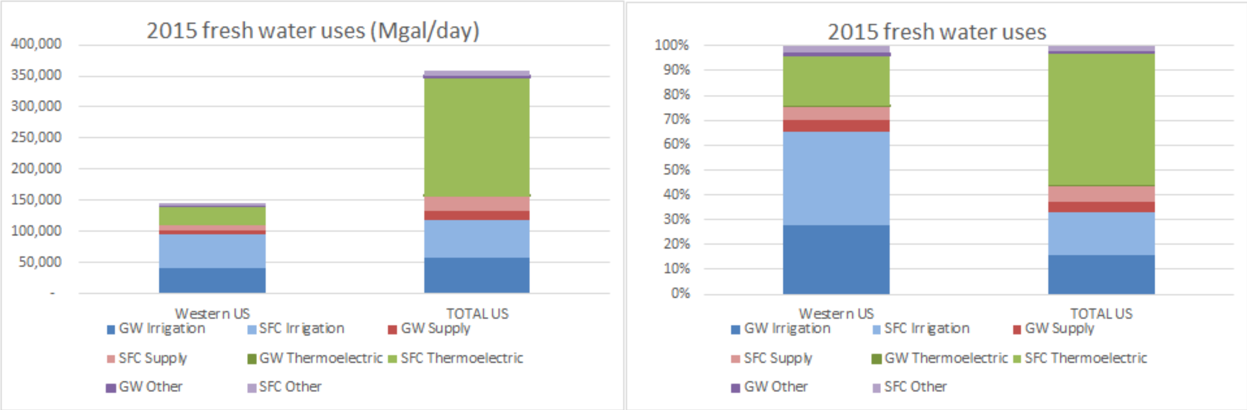

Figure 6. Distribution of freshwater withdrawals by source (groundwater versus surface water) and by uses (irrigation, domestic and industrial supply, thermoelectric plants, other) in absolute and relative values (left and right panels respectively). Source: Dieter et al. 2018.

Water availability in the western U.S. depends strongly on both natural and engineered processes operating across a range of scales and governance structures. Governance and operational realities of water management strongly control local water availability but are not consistently represented across agencies or modeling platforms. Driven by specific applications, there is considerable knowledge of regional water availability drivers (physical and human – engineered and governance) within the research and operational communities and associated agencies. Yet those drivers that influence water availability are conceptualized and managed through different research and operational user communities and are not consistently understood. Many coordination approaches focus on specific spatial or temporal scales, regions, and drivers, with complex representations of natural systems but simplified representation of human systems, or vice versa. Development of integrated science and supporting tools and data sets is also commonly not coordinated.

2.2.2 The Need for Integrated Forecasting

The challenges regarding water availability in the western U.S. result not only from water scarcity, but also from managing human activities with natural and engineered systems that span a range of spatial and temporal scales, along with associated governance. Out of simplicity, we categorize the research and operational needs along two temporal scales: short term (minutes to two years) and long term (beyond two years). Those temporal scales are strategic as they are associated with decision-making for operations and long-term planning.

Needs for Near-Term Forecasting

With water being over-allocated among users, and water storage and conveyance and transfer practices that may lead to high losses through increased evaporation and leakages, it is critical to better monitor, understand, and represent the engineering and natural system processes toward more efficient management practices. Specific needs include (1) the availability of observations for initial conditions, data assimilation, and evaluation with more relevant observations and faster access; (2) more accurate hydro-meteorological forecasts (snow, atmospheric rivers, monsoon); and (3) improved understanding of normal and alternative sectoral operations, such as aquifer recharge and overall surface water-groundwater interactions.

Needs for Long-Term Projection

It is critical to better understand (across institutions) the numerous underlying assumptions about how water availability will be stressed by changes in climate, water use, agriculture, population migration, and management practices to inform policy and adaptation strategies. It is also critical to make available observations from multiple, related sectors to better evaluate integrated assessment approaches.

For all decision-making, there is a need to coordinate observation networks, data sets, modeling tools, and assumptions across institutions/agencies toward more transparent and multi-institution, robust decision-making.

2.2.3 Exemplary Use Cases Demonstrating Progress and Potential

IHTM capabilities will provide significant benefits because they can accelerate the science that supports decisions to improve water availability and security in the western U.S. Below are several cases that demonstrate the envisioned benefits of IHTMs.

Colorado River Basin

The Colorado River Basin provides water to Wyoming, Colorado, Utah, New Mexico, Nevada, California, and Arizona, along with Mexico through the Colorado River Compact. All western U.S. states follow the prior appropriation water law (Figure 5.a, Gleick et al. 2011). About 80% of freshwater withdrawals support irrigation, which is derived mostly from surface water. The remaining 20% of freshwater withdrawals supports water supply, which also mostly comes from surface water (Figure 7). Correspondingly, several water agencies co-manage (states, U.S. Bureau of Reclamation [USBR], USDA, USACE) or support co-management of water availability through strategic research (NASA, NSF, USGS).

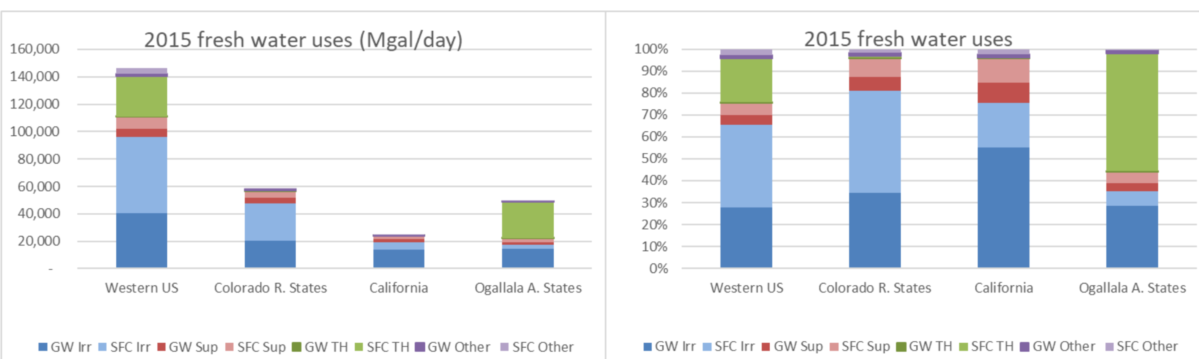

Figure 7. Regional distribution of freshwater withdrawals by source (groundwater versus surface water) and by uses (irrigation, domestic and industrial supply, thermoelectric plants, other) in absolute and relative values (left and right panels respectively). Source: Dieter et al. 2018. Note that some states (California, Colorado, New Mexico) are counted multiple times in this regional distribution.

Most of the water storage (scale of months to years) in the Colorado River Basin comes from perennial snow and groundwater storage. Large dams impound the Colorado River, providing multi-year storage for energy and water supply for the lower basin, at the cost of substantial evaporative losses and increasing water salinity levels. As of 2020, The Colorado River is in the worst drought in the historical record[1], where even multi-year storage cannot provide drought relief anymore. The recent 2019 drought contingency plan includes a shortage declaration in 2021 that would result in fallowing of half of agricultural lands in central Arizona.

Areas of research from a range of institutions include better climate forecasts, improved water storage monitoring, monitoring water movements between surface water and groundwater, and consistency in modeling approaches across political and basin boundaries. Engineering solutions, such as managed aquifer recharge, optimization of water releases for multi-water uses, irrigation technology innovation, and desalination are also active areas of research.

Some notable instances where an IHTM capability could make a substantive leap forward in the ability to manage water supply and quality are:

- **Gunnison River Basin:** The Gunnison River Basin contributes about 40% of stream flow to the Colorado River as it enters Utah and features some of the largest water storage infrastructure and federal water rights in the Upper Colorado River Basin. The river is managed for water supply and quality, power generation, recreation, and endangered species recovery, with these management objectives often in conflict. An IHTM capability would enable integrated assessment and scenario planning of water availability and quality for a multi-faceted stakeholder base that enables a predictive capacity to better ameliorate the consequences of climate- and population-driven changes in flows of water, nutrients, and metals.

- **Grand Lake, Colorado:** Both hydrology and operations impact the water quality in Grand Lake, Colorado, so operating this system optimally (for water deliveries and to meet water quality goals) requires a system that accounts for feedbacks between operations, watershed hydrology, and water quality. IHTM would integrate these models (or provide a smooth path for running them together) in a real-time forecasting application, which would provide needed information to better manage this system.

- **San Juan River Basin:** The electricity sector over the San Juan River Basin relies on water-dependent technologies to generate power and provide reserve services that support the reliability of the system. Agriculture relies on predictable water supply to define the reliability/revenue of the system. The allocation of water is influenced by multiple institutions defined by diverse stakeholders. IHTM would enhance the understanding of interactions between water users and managers across scales and better predict how the spatial resolution and complexity of "agents" can influence the definition of normal and beyond-normal operations.

- **Transboundary Basins and Trans-Basin Transfer:** In transboundary watersheds, forcing and parameter estimation data sets may stop or have marked differences at political boundaries. IHTM could facilitate collaboration among communities contributing data sets and methods used in modeling that support water management and planning. Awareness of how data may be used in the IHTM context, particularly in transboundary regions, could lead to more useful data development.

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[1] https://www.usbr.gov/newsroom/newsrelease/detail.cfm?RecordID=62170

Vast quantities of available data are not being made widely accessible or are not fully integrated and existing models do not incorporate all the processes, feedbacks, and legal structures. IHTM can be used to develop and evaluate strategic scenarios to respond to changes in climate, shifting human populations, increasing water demands, multiscale linkages between water uses, virtual water transfers, and economics.

California

Water resources in California support 39 million people and (mostly irrigated) agriculture that produces approximately $50 billion annually.[2] About 70% of freshwater withdrawals support irrigation, most of which comes from groundwater, although those estimates do not account for basin transfers from the Colorado River (Figure 7). About 20% of withdrawals support water supply and most of it is provided by surface water, which is managed for flood control, water supply for domestic and irrigation uses, and water quality in the Colorado River delta. Agencies engaged in supporting water resources management include the California Department of Water Resources (DWR), USGS, the USDA Agricultural Research Service (ARS), USBR, DOE, and NOAA.

California has the highest inter-annual variability in water availability of the western U.S. (Figure 5b). Snow storage is highly variable and decreasing due to climate change (Berg and Hall 2017). Groundwater has been extensively used to buffer this high variability, resulting in marked declines in water table elevations and groundwater storage, which in turn has caused subsidence and saltwater intrusion. Declining mountain snowpack has increased interest in investigations of managed aquifer recharge for wintertime water storage throughout the western U.S. However, physical and bureaucratic difficulties make optimization of a comprehensive groundwater portfolio difficult. The California Sustainable Groundwater Management Act (SGMA) was passed during the historic 2012-2014 drought (Griffin and Anchukaitis 2014). This act mandates that local groups come together to form Groundwater Management Agencies (GSAs) that will develop sustainability plans for water management in their region that, once approved, must be implemented within a 20-year period. The state maintains oversight of the plans and can take control of the process if acceptable plans are not submitted.

Mountain snowpack is one of the largest reservoirs for wintertime water storage, but annual mean snow water equivalent is projected to decline throughout the western U.S. by 20-40% by mid-century. IHTM could better integrate remote-sensing data and in situ data (similar to what has been done in California) to provide improved understanding of direct water runoff and water storage via snow. This approach, coupled with better seasonal temperature and rain predictions, should help water managers better plan for the timing of snowmelt runoff. More integrated models will also improve the understanding of pollutant flows through the water networks to ensure that water quality is fit for use.

Managed Aquifer Recharge (MAR), in which underground aquifers are replenished in the winter season using flood water, termed Flood MAR, is currently being considered as an avenue to recover some of the lost storage capacity from snow. IHTM would enhance the development of national data sets where groundwater storage can be recorded and managed. Coordination with meteorological projections on seasonal timescales would enable water managers to develop targeted water management strategies. Physically based models, including land surface, surface water, and groundwater models, need to be

[2] https://www.cdfa.gov/statistics/

coupled with water management models to accurately quantify water resource processes. For example, groundwater pumping rates are impacted by surface water management decisions, and groundwater pumping has a feedback on future surface water management decisions. IHTM could allow models to be more readily coupled, and for data to be exchanged time-step by time-step between models. IHTM would allow development of coupled streamflow modeling and facilitate testing of utilities for creating a spatial data repository tool kit for managing, accessing, and reformatting extracted information from very large spatial data sets so that these data could be used by modeling efforts across a wide range of disciplines.

IHTM would be capable of evaluating scenarios, including sustainable management, changes in natural and human systems, improved forecasts, declining snowpack with climate change, energy supply and demand, water rights, and economics, etc.

Ogallala/High Plains Aquifer System

Texas, Oklahoma, Kansas, Nebraska, and New Mexico rely heavily on groundwater from the Ogallala or High Plains aquifer. The High Plains aquifer system supports 20% of the total U.S. production of wheat, corn, cotton, and cattle and is key to U.S. food production today and into the future. Most of the water pumped from this aquifer is extracted for irrigation purposes (Figure 7 and Figure 8). This aquifer is over-appropriated: irrigated agriculture is the largest water consumer (94%), while thermoelectric power plants rely on large surface-water withdrawals but exhibit lower overall consumption. NASA's Gravity Recovery and Climate Experiment (GRACE) mission shows large reductions in water storage in the Central and Southern High Plains (Brena-Naranjo et al. 2014). Groundwater depletion is greater than 10 times groundwater recharge rates in the Central High Plains where water table declines exceed 30 m (Scanlon et al. 2010). If management of water in this system does not change, highly productive land could be abandoned in four states (Kansas, Oklahoma, Texas, and Colorado), potentially losing $2.2 billion per year. The state of Kansas recently allowed local stakeholder-driven groups to implement water conservation plans through Local Enhanced Management Areas (LEMAs). The pilot region for a LEMA, in northwestern Kansas, agreed to reduce its pumping by 20% over five years, through some combination of reducing the application rate, reducing irrigated area, and/or planting crops that use less water. This pilot LEMA reduced average pumping by over 30 percent with little reduction in crop yields, showing a positive path toward sustainable management. A much larger region recently approved a LEMA plan, providing a second test of the viability of this water conservation mechanism.

Figure 8. Map of the High Plains aquifer with classified irrigation areas from remote sensing from 1984 through 2017 (from Deines et al. 2019).

IHTM would help develop a better representation of both surface water and groundwater processes, agriculture, energy, and ecosystem interactions. IHTM would (1) help assess agroecosystem and human adaptation to groundwater; (2) identify groundwater availability to ensure soil retention as well as grazeable plants established and sustained, and (3) help define novel agricultural enterprises that maintain viability of traditional rural economics impacted by climate change.

Modeling tools for complex groundwater/surface water interactions are important for long-term water resources planning. In some regions, current tools are challenged by unique groundwater characteristics. Model output that differs significantly from observed data (e.g., modeled versus observed hydrograph) require significant bias correction, which may lessen confidence in results. An IHTM capability would increase the availability of interoperable models and model modules, which would offer a broader palette of components from which to address unique basin characteristics.

2.2.4 Desired Outcomes and Impacts on Science and Society

The desired outcomes of an IHTM capability as applied to the issue of water availability in the west include the following: (1) improving scientific understanding of how human, landscape, and water resource systems co-evolve; (2) better addressing institutional constraints and needs with products that matter to the public; and (3) advancing modeling to a scale that improves water management decisions, including those relevant to food and energy issues.

The workshop participants envisioned outcomes for near-term forecasting and long-term projections. Those outcomes and their perceived benefits to science and society are summarized below. For additional details, see the summary logic models produced from workshop materials (Appendix 3).

Objectives for Near-Term Forecasting

Identified objectives focus on developing collaborations among observation networks, and groups involved in data assimilation and model development. This collaboration will support the prediction of water availability and the understanding and accurate prediction of co-evolving/managed water-dependent physical and engineered systems.

1. Improve the consistency of representation of drivers influencing water availability within models used by various research and operational communities. Catalog modeling approaches with mission-specific underlying assumptions and representations. Work with regional stakeholders and agencies (federal, state, local) to better define modeling scope, needs, and potential for end use. Develop modular, interoperable models that enable representation of system components at varying levels of complexity as appropriate to each specific application.
2. Focus research on better understanding scale-dependent relationships in coupled human-natural systems as they impact water availability (e.g., model intercomparison, benchmarking, evaluation against observations, etc.)
3. Reduce data fragmentation. Improve monitoring networks to fill data gaps, share data in real time, and develop data standards to support multi-sector data exchange and analyses. Transition to open and interoperable scientific data management approaches.
4. Collaborate on observation networks, data assimilation, and model development to support near-term prediction of water availability that will enable scientific understanding and accurate prediction of co-evolving/managed water-dependent physical and engineered systems.

Objectives for Long-Term Projection

Identified objectives focus on the coordination between short-term prediction and long-term projection activities for water availability, including conjunctive surface and groundwater management, quality, and use. Effective coordination would help to better represent the adaptability of systems and support the development of long-term, resilient, hydro-terrestrial systems models.

1. Work toward a unified scientific basis for robust decision-making across agencies.
2. Develop an end-to-end community modeling framework for multi-sectoral application, linked to open data, that includes comprehensive uncertainty analysis. Integrate drivers across scales and sectors while accounting for differences in institutional governance.
3. Coordinate among agencies to develop future scenarios and improve resilience to change through integrated treatment of both supply and demand.
4. Develop sufficient fidelity (data and models) such that analyses and predictions are actionable at local decision-making scales.
5. Use open science capabilities that are evolving in a directed, non-ad hoc development cycle.

Overall, we anticipate that IHTM will contribute significantly in multiple dimensions of water security, food security, and energy security. The success will be built on greater focus and coordination among agencies to leverage funding and resources, as well as increased public trust. The community-wide integrated understanding and quantification of near-term natural and managed water availability drivers (e.g., physical, governance, operations) will support a range of applications (agriculture, energy, transport, etc.). The participatory environment should revolutionize how science serves society.

2.3 Water-Related Hazards

Extreme weather and climate-related hazards represent a priority water challenge within the United States. Droughts and floods are costly. Since 1980, 241 weather and climate disasters have cost the U.S. $1.6 trillion (NOAA 2020). Impacts from hazards include not only property damage and loss of life but also influences on the available water supply, disruption to navigation and thus commence, and potential harm to water quality.

2.3.1 The Current Situation

Climate change and ever-increasing anthropogenic influences, including land use change and water withdrawals, can exacerbate the hydrologic impacts, including droughts, floods (Figure 9), fires, landslides, and debris flows. These impacts stem from a complex set of interrelated systems, namely coupled weather/water/land interactions that include ecological processes, socio-economic drivers, population growth/migration, and expansion of the built environment. There is vast uncertainty in what physical changes might occur, how these changes will impact society, how society will adapt, and most importantly, what policy options will be most effective for mitigating the impacts.

Figure 9. Photograph of flood impacts. From U.S. Department of Homeland Security.[3]

Timely and accurate information is vital for recognizing vulnerabilities, mitigating impacts, coordinating emergency response, and initiating recovery associated with water-related disasters. Various federal agencies have expertise that is brought to bear. However, overlapping and divergent missions result in inefficiencies and information gaps. Consider the various water-related activities at the national level. The Federal Emergency Management Agency (FEMA) identifies flood hazards. The U.S. Army Corps of Engineers (USACE) manages flood protection. The USGS provides real-time monitoring of flow in streams and rivers while NOAA provides numerical prediction. The Bureau of Reclamation oversees water management in the west. The Department of Energy focuses on aspects related to hydropower while the EPA focuses largely on water quality. Each agency provides complementary information consumable by the other agencies, yet each agency operates its own legacy systems tailored for its particular mission/purpose. Data are available or shared in some locations and wholly lacking in others. Further, each agency develops its own software packages that ingest data that are frequently separated by institutional firewalls. This disjointed framework makes it difficult, if not impossible, to adequately address water problems as a whole. Compound flooding events are particularly vexing. These are the combined result of simultaneous fluvial (river flow), pluvial (rainfall), and coastal (storm surge) processes. Although each process is fairly well understood individually, their compounded effects are generally not yet considered in loosely coupled, or offline, modeling systems.

2.3.2 The Need for Integrated Forecasting

The science underlying flood response and water resource management is complex and spans mission boundaries. Multi-agency coordination is essential to extend the national capability for prediction and scenario building and bring the latest research into operations. This is critical in order to adequately address the Nation's priority water challenges and collectively advance the water-related missions of individual agencies. Given a changing climate and uncertain hydrologic and human response, we need far-field projections of future hydrologic events and related impacts. A comprehensive framework is

[3] https://www.ready.gov/floods

required to analyze the frequency, distribution, and intensity of extreme weather and hydrologic events, and the resulting impacts on infrastructure, water supply, and water quality. An Integrated Hydro-Terrestrial Modeling (IHTM) approach is needed to conduct process studies and simulations, assimilate real-time information, leverage hydro-meteorological and climate forcings, and provide medium- and long-term forecasts that can help decision-makers address imminent challenges.

Needs for Near-Term Forecasting

The critical objective for near-term hazards forecasting is high-impact hydrologic models that can provide near-term warnings and decision support. Improved process understanding and coupled process modeling approaches could help to overcome current limitations in actionable hazard intelligence. For example, spatial and temporal mismatches exist between atmospheric, water, and land processes that result in undue computational burdens and/or lost precision. However, transitioning the latest research to operations can be costly and time consuming. Improved interoperability of data and models (e.g., standardized data, common application programming interfaces [APIs] and libraries, enhanced and consistent initial states and scenarios, and life-cycle management processes that facilitate model reconfiguration) would dramatically reduce barriers to the R2O2R pipeline.

Needs for Long-Term Projection

Long-term projections require improvements in (1) understanding and model representation of process linkages that create complex outcomes, (2) better understanding of system tipping points (conditions that lead to a significant shift in system responses), (3) improved quantification and communication of predictive uncertainty, and (4) ability to drive local model predictions with down-scaled inputs derived from global or regional climate model outputs. Addressing these needs requires fundamental process research as well as integrated data and modeling systems. The ITHM capability must overcome fragmentation of data and models among agencies through development of agile interoperable frameworks that reduce barriers associated with legacy monolithic code bases. An open science approach to interagency cooperation (Chapter 7) is critical to achieving this objective.

2.3.3 Exemplary Integrated Use Cases

Breakout discussions at the workshop, as well as the Exemplary Integrated Use Cases submitted prior to the meeting (Appendix 3), brought to light a wide range of extreme event concerns. Some recurring themes include:

- Impacts of complex and interrelated events
- Flooding
  - Complex coastal/river/overland/water management
  - Interactions among, including failure of, urban infrastructure
- The impacts of fire on hydrology and debris flows
- Droughts/water supply
- Frozen ground/permafrost thaw/infrastructure failure
- Sea-level rise, saltwater intrusion, and water quality.

Selected situations are discussed below with references to the relevant integrated use cases provided.

Complex/Interrelated Flood Events

Different agencies and groups within agencies focus on different types of flood events and different types of hazards. For example, a primary focus of the USACE is reservoir stages and emergency operations of reservoirs during flood events, while NOAA may focus on flood and flash flood forecasting across the country. Whether these types of activities focus on one system and one flood hazard, or on events across the country, they share two main elements in common: 1) the systems that are being analyzed and forecasted are governed by a complex set of interrelated factors and physical processes, and 2) the modeling frameworks being used often do not adequately capture the complexity or coupled nature of the system to support optimal decision-making.

A prime example of complex flooding is the extended event impacting the Lake Champlain-Richelieu River system (Appendix D, Use Case 48). Here a combination of large inflows, wind-driven waves, and storm surge are causing lakeside and downstream compound flooding. Another example centers on flooding from Hurricane Irma across Florida related to rainfall, storm surge, extreme lake levels, and other causes (Appendix D, Use Case 53). These events are not isolated, with many coastal regions prone to flooding due to storm surge, intensive rainfall, and high river stages during tropical and extratropical events (Appendix D, Use Case 49). An illustration of this is the recurrent compound flooding in Miami-Dade County (Appendix D, Use Case 49) during similar conditions that can be exacerbated by high groundwater levels. Compound flooding can interact with other natural processes to become even more devastating. During a wintertime Nor'easter, for example, flooding is influenced not only by the factors noted above, but by river ice jams, rain-on-snow melt, frozen ground, reservoir regulation, groundwater, and urban factors (Appendix D, Use Case 43). The resulting flooding can impact water quality, causing sewer system overflow and agricultural runoff. These combined factors drive the need for an integrated and fully coupled process modeling system.

Sea-level rise is expected to make flood-related problems worse in coastal regions, with areas highlighted in use cases of the Mid-Atlantic, Miami-Dade, and regions in the Northeast, including the Delaware River (Appendix D, Use Case 6). Focusing on one of these issues or systems in isolation is not sufficient because the systems interact, and flooding may occur due to unexpected hazards unless all potential hazards are considered in an integrated fashion. Communities that experience these issues are well aware of the situation and are ripe for engagement in the process of developing the IHTM. An interagency community of practice (CoP) dedicated to this issue would provide a natural outlet for this type of interaction. Stakeholders would help the CoP define their requirements. The CoP could also look to longer-term goals, like determining suitable test beds where model interoperability could be developed and tested.

Watershed/River/Reservoir/Groundwater Systems Management

Many agencies are involved in some aspect of water systems management, be that surface water in the form of rivers and/or reservoirs or groundwater, or possibly both. For instance, the USACE operates reservoirs and other in-stream systems for flood control and other authorized purposes, such as water supply, electrical generation, etc. During extreme flooding events the USACE may use flow/stage forecast from the National Weather Service local River Forecast Centers to augment operations. The Mississippi River and Tributaries Project, along with reservoirs throughout the Ohio-Mississippi River, is the largest flood risk management system on the planet (Appendix D, Use Case 50). In addition to the size and complexity of the system, management is complicated by the need to support navigation, as the system is a major freight route for industry and agricultural products. In South Florida, the South Florida Water Management District and the USACE manage a complex system of canals and structures to provide flood control for low-lying regions such as Miami-Dade, where many people live roughly a meter above high tide (Appendix D, Use Case 49; Figure 10). Recent floods in the Lake Champlain-Richelieu River system due to high inflows, storm surge, and wind waves required releases from Lake Champlain that worsened downstream flooding (Appendix D, Use Case 48). Similar issues affect the Great Lakes (Appendix D, Use Case 54), which are complicated by the need to maintain the lake levels for navigation, water supply, and recreation. These complex water management activities need to be accurately represented within modeling frameworks and supported by an associated integrated stream of regulation observations in order to produce accurate flow, flood, and water resource analyses (Appendix D, Use Case 43 and others cited above).

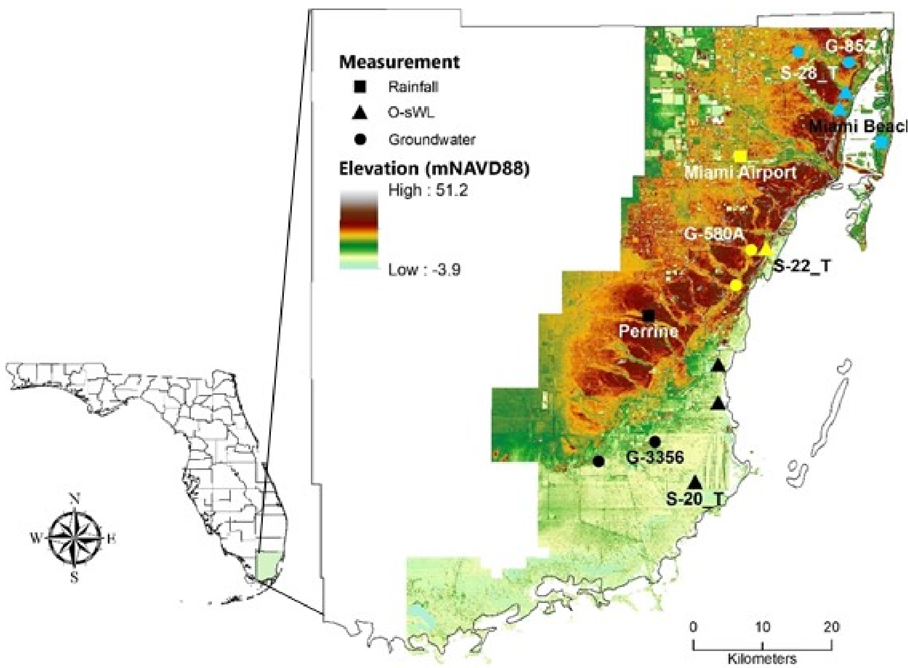

Figure 10. Left: location of Miami-Dade County in the state of Florida, USA. Right: topographical map of the eastern portion of the county with locations of measuring stations for compound flooding drivers, including ocean water levels (O-sWL), groundwater, and precipitation at three case study sites (differentiated through color). From Jane et al. 2020.

Issues of systems operations go beyond just the immediate risk of flooding. Systems are operated for multiple purposes, such as water supply, and the threats may be slower moving and less obvious, but no less real. In the Delaware River Basin (Hazards Use Case 14), releases of fresh water from reservoirs are required to lower salinity levels from intakes that supply water to over 15 million people and 11 cities, including Philadelphia. This system is threatened by rising sea levels and increasing salinity in the estuaries. The threats go beyond surface water to include groundwater. In the Delaware Bay (Appendix D, Use Case 6), groundwater supplies 40% of the regional drinking water supply, and the system that supplies this water is under threat from rising seas and increasing salinity in shallow aquifers. Groundwater issues may be intertwined with the surface water system, complicating the issue. The Upper

Rio Grande Watershed (Appendix D, Use Case 34) is such an example where surface water management decisions affect groundwater pumping and the groundwater pumping rates affect surface water management decisions. Water regulation and water management also profoundly impact water quality. Growing issues with harmful algal blooms (Appendix D, Use Cases 18 and 48) emphasize the need to adequately model water management systems and the broader hydrologic system in general.

Decisions made for flood control or other types of operations may affect the integrity of the system, leading to failure, or exacerbation of existing problems, such as changes to the hydrology due to climate and land use change, aging infrastructure, and delayed maintenance leading to loss of storage in reservoirs due to sedimentation, lost capacity in channels due to sedimentation, plant growth, and other reasons. The USDA (Appendix D, Use Case 35) identifies this as a national issue.

An IHTM capability would aid the operation and maintenance of managed systems in several ways. It would pool intellectual resources from multiple agencies for operation and maintenance budgets and allow better coordination between agencies in the operation and maintenance of systems. Leveraging this coordination, the IHTM capability would also be better equipped to represent the complex and interrelated processes via coupling of relevant process models and ingestion of appropriate real-time water management data sets. The IHTM capability could be used to inform both short-term emergency management, and long-term system management and maintenance decisions. Since data are critical to systems operations, a great short-term goal to address this issue would be data sharing among the agencies. A natural longer-term goal might be a shared enhanced data network.

2.3.4 Desired Outcomes and Benefits to Science and Society

An important element of the IHTM vision is an assessment tool that can be used by policy and decision-makers to both understand and prepare for possible future conditions. Output from an IHTM capability will enable end users − water managers, federal, state, and local planners and others − to take proactive steps to mitigate projected impacts from future floods and other hazards. We envision that the system will enable users to game potential climate/weather/hydrologic scenarios and test potential mitigation responses, such as structural approaches, resilient infrastructure, and emergency response preparation. Potential near-, medium-, and long-term goals/activities and products identified during the workshop are listed in Table 1.

The workshop participants envisioned outcomes for near-term forecasting and long-term projections. Those outcomes and their perceived benefits to science and society are summarized below. For additional details, see the summary logic models produced from workshop materials (Appendix 3).

Table 1. Near-, medium-, and long-term goals/activities/products.

	Near-Term	Medium-Term	Long-Term
Data management	Data sharing	Comprehensive data stores; data management systems	Automated dissemination; human/machine readable
Standardization	Community standards	Common test beds; standardized workflows; model interoperability	Modular, reconfigurable, modeling system
Products	Network of critical observations and forecast points	Enhanced observation network; probabilistic forecasts; impacts	Actionable local-to-national water intelligence; Risk-informed decisions
Activities	Stakeholder engagement; define requirements	Performance assessment and benchmarking	Uncertainty quantification; apply AI/machine learning
Innovations	Improved resolution and fidelity; common operating picture	Incorporate longer timescales	Identify tipping points; assess water quantity, quality, and sediment budgets
Governance	Communities of practice	Investment in life cycle management	Inform policy

Outcomes for Near-Term Forecasting

Key outcomes for near-term forecasting of water-related hazards focus on the development of enhanced decision support and information tools to increase public safety and protect economic assets. A well-informed, event-ready public will not only save lives and protect property, but also minimize societal disruptions and facilitate commerce.

1. Advances in data science, computational efficiency, and model synchronization will strengthen reproducibility and consistency across models and allow us to answer more challenging and complex questions.
2. Interoperability of modeling frameworks across agencies will reduce time needed to incorporate research results into applied tools. Use of more sophisticated, quality-controlled, and cross-domain data sources will lead to improved water quality monitoring, forecasting of social impacts, and water security.
3. Community investment (training and information sharing) will develop informed scientific understanding and, in combination with improved capability to explore complex model uncertainties, will lead to actionable water intelligence at local to national scales.

Outcomes for Long-Term Projection

Key outcomes for long-term projection of water-related hazards focus on developing improved understanding of processes, interactions, feedbacks, and overall dynamics of complex integrated hydro-terrestrial systems, which will lead to improved model predictive skill. The availability of more powerful predictive tools for long-range planning and development, spanning a wide range of sectors and user communities, will improve water security, safety, economic conditions, public health, and natural resource management decisions.

1. The envisioned system will allow multi-disciplinary integration of information across agencies and communities within interoperable modeling frameworks including socio-economic and geopolitical considerations. The system should be available and accessible to all and flexible to accommodate innovative approaches (e.g., artificial intelligence to understand "unknown unknowns").
2. Improved long-term projections will enable identification of a range of possible outcomes including potential tipping points, facilitating improved water policy.
3. The evaluation of impacts of long-term trends (e.g., social, economic, and climate) will be enabled by the ability to run and evaluate complex meaningful scenarios at a range of appropriate spatial and temporal scales.

3. Data Management, Community Platforms, and Standards

Individual practitioners or institutions tend to have their own data creation and management practices, driven by their own mandates, historical protocols, and the organic evolution of data content and information technology. This results in a wide diversity of types, practices, and models for characterizing and handling data, which significantly hinders reproducibility of science and reuse of data. The IHTM community has an opportunity to accelerate and improve our science by deliberately focusing on development and adoption of common best-data-management practices for modeling information.

3.1 IHTM Vision for Data Management, Community Platforms, and Standards

Community-wide identification, development, and adoption of standard practices for data management is an important basis for sharing scientific knowledge across the IHTM community. Using community platforms in ways consistent with the concepts of open science has been identified as a key method for developing new ideas, building consensus, and communicating practices across the agencies and broader IHTM community.

Goals for IHTM data management include:

- Improve efficiency and appropriateness of model development and application by ensuring that data are easily discoverable and widely accessible
- Establish data repositories to support easy use/reuse of IHTM content
- Improve capacity for collaboration (communication, resource sharing, education, and focused research and development) through establishment of community platforms and tools
- Develop pathways to maintain and modernize existing data and to create new data according to best practices for data management.

3.2 Making It Happen

Although convergence of missions across institutions would greatly help development of common best practices for data management, this is not a requirement. Standards for data, metadata, and workflows are beneficial to individual practitioners and institutions. IHTM needs to support the community process of establishing new or extending existing standards and follow through by driving adoption of standards to realize benefits from them. An effective way to encourage this will be by developing a cross-institution data management community embedded in the broader Earth systems information community. This IHTM-focused community of practice could provide systems, tools, and training to practitioners on their use in workflows that leverage these standards to support their business needs (data analyses, visualization, and geospatial analysis).

Although also addressed in other parts of this report, supporting the social component of collaboration (developing and deploying best data management practices and infrastructure) is mentioned in order to introduce community platforms that, as entities that share practices and work together, significantly promote development of an IHTM capability. These platforms are used for sharing data, software, and workflows, tracking issues, managing communication, and accessing shared computing resources. More importantly, this is a vehicle for practitioners to interact with each other. It is important to note that financial and institutional support for facilitation, user support, and outreach is considered a critical component of a successful platform.

3.2.1 Overcoming Barriers

Perhaps the most substantive barriers to the use of standard data management practices across IHTM will come from differences in institutional policy, technology, culture and practice as well as from stakeholder expectations and requirements. While data management at all federal agencies and many other institutions is influenced by general concepts, such as the FAIR (**F**indable, **A**ccessible, **I**nteroperable, **R**eusable) data principles (https://go-fair.org/fair-principles/), and is explicitly unified by requirements of various U.S. Government policies, such as OMB Circular A-130, "Managing Federal Information as a Strategic Resource" (https://whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A130/a130revised.pdf) and The Geospatial Data Act of 2018 (P.L. 115-254; summary report) (https://crsreports.congress.gov/product/pdf/R/R45348), implementation of these and similar requirements is, at best, handled inconsistently. This is especially true when these general guidelines and policies are applied to specific domains, such as those of ITHM, where extensions and modifications are frequently needed.

To overcome these barriers, IHTM member agencies/institutions need to commit to creating an internal infrastructure of policy, technology, and communication that helps individual science practitioners to apply community practices and resources to their own work. To maximize benefit of the IHTM collaborative science vision to institutions, this infrastructure must be engineered to interoperate with those of other IHTM members. It is important to recognize that these issues are not chiefly technological. For example, the seemingly simple idea of sharing computing resources can be constrained by network security and user credential requirements; these requirements cascade from bureau or department policy.

3.2.2 Roadmap for Progress

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (4-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Near-Term Goals and Activities

Near-term goals for IHTM data management, community platforms, and standards include:

- Establish a governance and business model for IHTM community development and adoption for data management.
- Produce a roadmap for IHTM data management, including pathways for adoption by participating agencies/institutions.

- Share existing protocols, workflows, and tools for data analysis/filtering/mining/visualization of content through repositories. Identify gaps and prioritize solving these.
- Prioritize gaps in uptake of existing standards and best practices; develop tools to improve adoption. For instance, hydrometric standards exist but should be in wider use.
- Prioritize and fill gaps in existing standards. Standards for hydrologic and geologic data exist but are not sufficient. Needed standards for hydraulic/hydrodynamic data are largely non-existent. Other domains, such as ecology and biology, need to be evaluated.
- Establish logins to shared computing platforms, code, and data repositories. This requires policy harmonization beyond the technical issues of identity authentication.
- Sponsor an IHTM "user conference" to bring together domain (i.e., Earth) and computer scientists.

Mid-Term Goals and Activities

- Establish an initial ecosystem of IHTM community-based standards and best management practices. Fund and promote these practices through outreach/training to drive adoption. Continue to fund testing and evolution of standards.
- Develop thinking for transition from initial focused work groups; shared data, tools, and infrastructure; and best management practices into standard operating procedures for the IHTM community.
- Implement the first generation of shared and widely used technical infrastructure (data storage, compute capacity, catalogs).

Long-Term Goals and Activities

- Develop standards for hydrography, hydrodynamics, hydrology and hydrologic modeling, and other relevant domains, that are incorporated in those of broader organizations, for example, within the Open Geospatial Consortium WaterML2 suite of standards.
- Develop and implement mechanisms for member agencies to routinely share and reuse models and data created through the IHTM communities to fulfill their missions.

3.3 Benefits to Science and Society

A robust data management community underpins almost all the other goals described in this report. Application of standards-based best practices provides clarity about data (and model) meaning, integrity, accuracy, and consistency; minimizes redundancy; maximizes reusability; and documents business rules. Impacts on the scientific community of a deliberate, sustained community data management approach include enhanced discovery and more efficient and appropriate reuse of scientific knowledge (data, methods, tools) and accelerated development of new knowledge. Robust standards and collaboration platforms will improve the ability of the IHTM community to communicate many kinds of information internally and externally. This will benefit society, ensuring that decision makers are better informed through access to the best available information, resulting in better management of natural, financial, and other societally important resources.

4. Software Engineering for Interoperability and Sustainability

Modeling of natural processes and anthropogenic effects on the natural system has become a common approach used by federal agencies to answer questions related to their defined missions. The overlap between agency missions, while admittedly addressing different stakeholder needs and agency requirements, has generated considerable duplication of software development efforts. For example, software solvers for one-dimensional flow in river networks have been developed by several national laboratories, the National Weather Service, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Department of Agriculture, and the U.S. Geological Survey. Duplication of effort has also occurred for fate and transport models, integrated surface-water/groundwater models, multi-dimensional hydrodynamic models, reservoir models, unsaturated zone flow and transport models, watershed models, etc. Duplicative effort by federal agencies increases the cost to U.S. taxpayers, restricts software capabilities to those developed within the agency, and limits the types of problems that can be addressed within each software ecosystem.

4.1 IHTM Vision for Software Engineering

The IHTM vision for future software development activities at federal agencies is to develop component-based processes with inherent interoperability (Figure 11) using modern software development practices (Figure 12). The component-based processes will be linked together using a common component management module, allowing for code reuse or extension where appropriate, and will be able to access forcing data from external sources or other components using a common data management module. Other key aspects of the IHTM software include a common workflow management module to standardize common workflows and a common toolbox for managing and analyzing component input and output.

We expect that current codes with unique capabilities or with substantial user communities will be refactored to become part of the IHTM ecosystem of component process models. However, the design above is intended to enable such a refactoring process with minimal invasiveness towards existing ecosystems or workflows. The combined system is expected to enable robust and automated configuration of IHTM components within a unified, coherent framework that will leverage the capabilities and contributions from multiple federal agencies and national laboratories. Ultimately, bringing modeling activities of multiple federal agencies under a common IHTM umbrella will reduce the cost of software development by enabling coordinated efforts, expanding the set of possible model analyses, and allowing the next generation of component process models to be part of a larger vision.

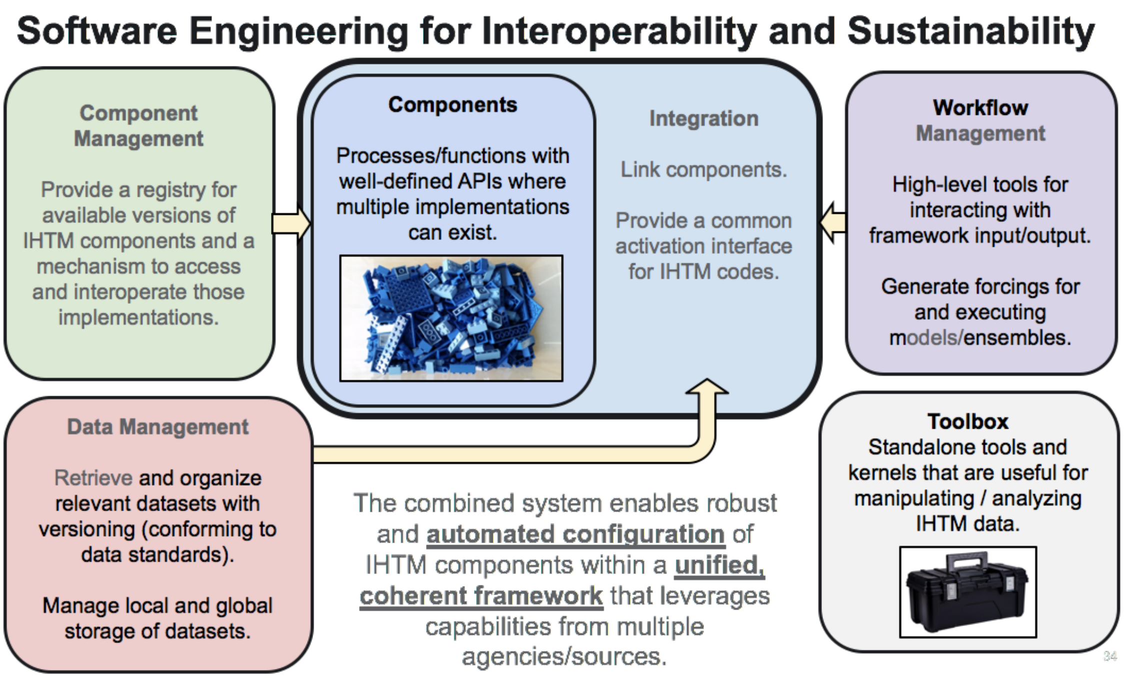

Figure 11. IHTM vision of a component-based interoperable software ecosystem with data and workflow management components and a robust toolbox for manipulating and analyzing data. Components are expected to include refactored versions of current codes with unique capabilities or substantial user communities.

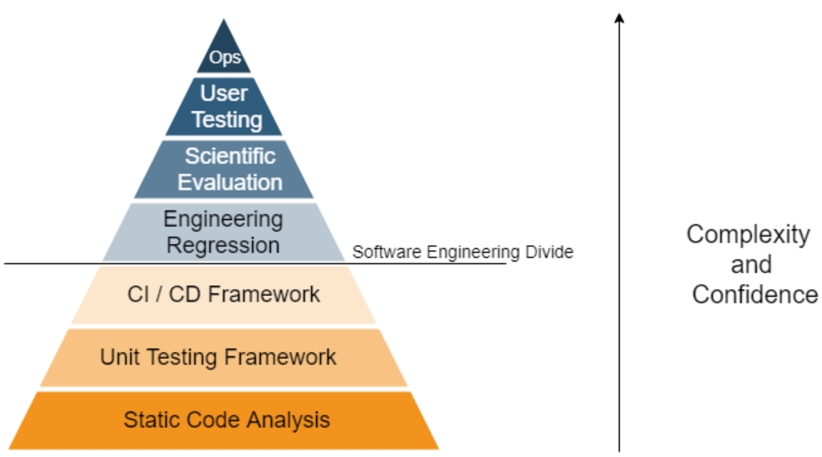

Figure 12. Modern software engineering practices including code analysis, unit testing, continuous integration (CI), and continuous delivery (CD) produce robust, defensible, and extensible software. Modern software development practices also include opportunities for scientific testing of components and user testing to improve software functionality. There are opportunities to better integrate foundational software engineering methods (below the "Software Engineering Divide") and use-focused testing (above the Divide), for example, to allow feedback from scientific evaluation to support design of unit tests.

4.2 Making It Happen

Implementing the IHTM vision will require buy-in, commitment, and sustained investments from federal agencies and, in many cases, will require modification of agency policy to allow development and use of open-software practices. It is also likely that federal agencies' policies will have to be modified to permit the use of open-source software with components developed by others to address mission questions. In general, the success of the IHTM effort hinges on incentivization of open software development by software engineers and domain specialists within the agency space.

4.2.1 Overcoming Barriers

Software interoperability is the ability of software developed by different federal agencies and national laboratories to exchange and use functionality and data. An example is runoff generated by a landscape model being used as forcing data by a one-dimensional river network model. The current software practices and ecosystems have evolved within federal agencies to address specific issues within each agency's mission. As a result, existing software packages are fragmented (siloed) and often cannot be used together (are not interoperable), which limits the ability to apply the software to problems that leverage capabilities from multiple agencies and also limits the ability to address current and future problems with the necessary degree of coupled process complexity. Current agency practices make software development time consuming and expensive. Existing software ecosystems have limited discoverability, interoperability, and availability. Significant time is spent duplicating existing capabilities, components, kernels, and tools. Many different codes are used across agencies, but often cannot be used together (even within federal agencies). Domain scientists, with limited understanding and use of modern software engineering practices (Figure 12), have developed siloed codes or cumbersome frameworks. Resolving fragmentation and interoperability issues will require the development and adoption of interface and data standards and support for those standards by participating federal agencies and national laboratories.

4.2.2 Roadmap for Progress

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (4-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Near-Term Goals and Activities

- Develop and adopt standards for interoperability, documentation, and testing. To the degree possible, existing industry standards will be used (for example, Open Geospatial Consortium [OGC)] Cloud Native Computing Foundation [CNCF], World Wide Web Consortium [W3C], etc.). If existing industry standards do not meet IHTM software needs, to the degree possible the IHTM team will work with the developers/maintainers and scientists to extend existing standards rather than develop a new standard.
- Adopt sustainable open-development practices for IHTM software development activities. Open-development activities would include a comprehensive unit and integration testing framework.

Development practices would also include an IHTM code style, implementation standards, and automated documentation development.

- Review and adjust agencies' policies to allow open development of IHTM software.
- Recognize and incentivize open-development contributions.
- Develop a software working group to define IHTM collaborator capabilities and needs. The working group includes liaisons from relevant IHTM groups, open science design group, and academic/agency software engineer representatives. The working group's charge will be to increase componentization and facilitate sharing; identify capabilities and gaps in current agency software products; determine work required to generalize capabilities and fill gaps; develop standards for interoperability, documentation, and testing (an iterative process); and work with software engineers implementing standards in existing agency software.
- Adopt open-development practices for IHTM software development activities.

Mid-Term Goals and Activities

- Regularly review and adopt community-developed/adopted standards.
- Implement language interoperability for IHTM components.
- Develop protocol and message exchange standards.
- Expand support for a wide range of computing resources, from laptops to supercomputers.
- Develop the runtime-configurable, component-based modeling ecosystem.
- Develop or identify low-level tools in the IHTM software ecosystem toolbox. Low-level tools include tools for re-gridding, controlling simulation time, etc. An example of an existing system is the Earth System Modeling Framework (ESMF), which includes tools for re-gridding data. As with the IHTM standard, the preference would be to use an existing system and work with developers to extend that system to include capabilities needed in the IHTM software ecosystem.
- Regularly review standards and develop a community of developers and users that extends beyond the initial early adopters through training and presentation of IHTM software and application results at scientific conferences.
- Apply IHTM software to select use cases on hardware ranging from laptops, to cloud applications, to exascale supercomputers.

Long-Term Goals and Activities

- Develop the complete IHTM software ecosystem that includes multiple interoperable process components, a component management system, a data management system, a workflow management system, and a comprehensive toolbox for managing and analyzing component input and output.
- Produce a system that enables robust and automated configuration of IHTM components within a unified coherent framework.
- Design discoverable process components with consistent, detailed documentation.

- Recover and refactor legacy software into the IHTM software ecosystem. This will extend the lifetime of existing software with a significant user base and leverage previous development activities by IHTM participants.
- Build a self-governing and fully functioning community of practice among IHTM software ecosystem developers and users.
- Apply the IHTM software system to:
  - Hypoxia, excess nutrients, and harmful algal blooms use cases (Section 2.1)
  - Water availability in the west use case (Section 2.2)
  - Flooding and extreme water hazards use cases (Section 2.3).

4.3 Benefits to Science and Society

An IHTM framework will benefit society by enabling flexibility for simulating and analyzing known stakeholder use cases. Society would also benefit because the IHTM framework would bring comprehensive modeling capabilities to stakeholders and the public in a transparent, well-documented, and actionable framework.

Science would benefit from the IHTM framework as a result of an enhanced ability to produce and analyze hydro-terrestrial model data. The IHTM framework would reduce redundancies between agency investments, leverage the distinct strengths of contributors, and allow users to focus on science questions instead of technical details. It is expected that the IHTM framework will lead to faster, deeper science and applications that expand the scope of processes and couplings evaluated as part of future scientific studies.

5. Cross-Disciplinary Workflows: Analysis and Evaluation

Workflow toolsets are a key instrument for integration of different model codes and for working across agencies. Workflow toolsets are codified procedures, often using scripting language, that (1) provide a template for analysis and modeling and (2) allow for repeated execution of a set of steps in modeling and analysis. Workflows can connect disparate data sources to model components that need them and foster repeatability, which can lead to more reproducible science. Workflows also provide guardrails of best practices and can provide defensible starting points for integrated modeling and analysis. Importantly, efficient workflows facilitate the process of uncertainty characterization, which typically requires tens of thousands of repetitions of workflows. Currently, many agencies and organizations have workflow tools but they tend to be specialized and fragmented. A focused IHTM collaboration can unify agency approaches, build upon the existing workflow tools, and innovate intentionally for workflows not yet available.

5.1 IHTM Vision for Cross-Disciplinary Workflows

We envision a unified modeling platform with tools for data handling, simulation, post-processing, and visualization. This platform would provide access to data sets across agencies and would integrate existing agency-specific workflows into a unified and discoverable repository. IHTM workflows could accelerate the production of actionable science and increase trust in results by explicitly capturing connections and dependencies among multi-agency data, code, and tools.

This vision supports cross-agency collaboration on complex large-scale data sets, efficient and consistent uncertainty quantification, large exploratory computational experiments, and integrated post-processing steps such as statistical model evaluation. Bringing the computing and data resources into proximity also improves overall efficiency, lowers barriers to entry for up-and-coming scientists, and enhances repeatability and reproducibility.

5.2 Making It Happen

Implementing the IHTM vision should start with evaluation of existing scientific simulation and data integration workflows across agencies. With understanding of how each agency currently structures its work, we can then move toward development of shared data and code standards to enhance interoperability and develop joint workflow structures that will provide necessary flexibility to meet individual agency needs while also providing a framework for efficient problem solving in a repeatable and transparent manner.

5.2.1 Overcoming Barriers

Both technical and institutional barriers in agency administration and culture impede progress toward an integrated workflow toolset.

The technical barriers include the fact that disparate and fragmented workflow tools already exist as do a variety of computing environments across which workflows must function. Data sets and formats are not centralized or standardized. Furthermore, uncertainty quantification is often an afterthought in modeling projects and can be complicated by complex and computationally intensive workflows. Unifying efforts around a cohesive workflow framework and encouraging best practices, including data assimilation and uncertainty analysis, will require significant effort.

The institutional barriers to workflow development resemble those impacting other aspects of IHTM. In particular, individual agencies need to meet their existing and future mission needs and the current set of specialized tools have been developed for agency-specific tasks. Agencies also need to always demonstrate that the resources sent to them are fulfilling their mission, which requires credit and attribution for collaborative efforts. This can be challenging in an integrated framework. Additionally, existing workflow frameworks and best practices have been established by individual researchers, groups, and agencies. Agreement on the best paths toward repeatable and rigorous workflows are not necessarily uniformly agreed upon. Negotiation and discussion are required to bring these together.

5.2.2 Roadmap for Progress

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (3-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Near-Term Goals and Activities

- Start with what already exists. Assess existing open-source capabilities and identify gaps in versioning, data standards, data assimilation and uncertainty quantification practices, and other existing tools and frameworks.
- Explore data standards to enhance interoperability so that workflows can be tailored to the data formats that will be used.
- Build and strengthen relationships with users and stakeholders to ensure minimal disruption of existing workflows and relevance of new software tools.
- Start to establish governance to manage the interagency cooperation in a formal way.
- Create interagency workflow prototypes.
- Develop guidelines for model output storage and reproducibility.

Mid-Term Goals and Activities

- Formalize agreements for data sharing among agencies.
- Establish and use governance to formally manage the interagency cooperation/collaboration.
- Develop application programming interfaces and data and code standards to enhance data sharing and connections of codes to workflows.
- Start building libraries and tools as a community with common standards and practices.
- Formalize interagency relationships to promote co-production.

Long-Term Goals and Activities

- Sustained, seamless delivery of scale-relevant model results in a time-relevant manner.
- Generalizable, scalable, efficient, reusable workflows for hydro-terrestrial modeling.
- Collocated open data and compute resources for efficiency and repeatability.

5.3 Benefits to Science and Society

Benefits to society include rigorous, repeatable pathways through data analysis, modeling, and interpretation, including assimilation of relevant data and formal reporting of limitations through uncertainty quantification. These pathways can lead to more efficient hypothesis testing to the benefit of science and more accurate prediction/projections to the benefit of society. Repeatability enhances credibility and transparency to the scientific enterprise, which increases public trust in the results. Workflow tools can also reduce the barriers to entry for new research by decreasing the time spent setting things up and the number of tools and skill sets needed to set up complex workflows. This can greatly accelerate the pace of discovery for faster and deeper science and iterative hypothesis testing. Finally, workflows shared among agencies lead to more holistic and interdisciplinary cooperation which, in turn, fosters improved communication, better decision-making, and acceleration of the R2O2R cycle.

6. Building Computational Testbeds

The IHTM user community requires the ability to collaborate in a cross-agency manner on the development of joint or sequential numerical modeling software systems, necessitating the establishment of a community computational testbed or system of interconnected testbeds. A community testbed enables collaborative modeling and supports teams to work together to jointly develop IHTM components and rapidly share or access data delivered by one IHTM component to initialize downstream components.

6.1 IHTM Vision for Building Computational Testbeds

The vision for an ITHM computational testbed includes either (1) a single large computing system that every participating organization and individual can access, or (2) a collection of computational systems networked across participating government centers that supports rapid data transfer; joint software development, compiling, and testing; and open science standards. The testbed needs to consist of scalable architecture and enable a wide variety of options from small, single-threaded application development to cloud infrastructure to large-data, large-memory, distributed software systems that use high-performance computing methods. The system will also need access to automated data pipelines connecting sensors to databases to simulation platforms, support rapid data transfer across networks, and/or have the ability to pull in data from the broader scientific computing community.

An ITHM computational testbed supports community-driven development and testing to build better multi-scale models that support decision-making. The testbed will enable developers with a common software environment and a common set of evaluation protocols and data sets for component and integrated testing. A collaborative testbed also facilitates efficiencies with common visualization and data analytic tools specifically engineered for the IHTM mission and allows for more effective dissemination of demonstration products to stakeholders and interested participants. The testbed ideally would provide staff and training (both domain and computer scientists) for user support and have a robust governance process with representatives from all participating IHTM organizations. Properly managed, the community IHTM testbed would provide a key linkage between participating members and allow agencies to leverage community resources for rapid transition of research to operations (R2O) while also supporting the transition of information, needs, and capability from the operations-to-research (O2R) community. The envisioned computational testbed should possess the following attributes:

- Support for big-data, big-memory computing software systems.
- Enable execution of ensemble-models, potentially including hundreds of simultaneously executed large-memory, multi-processor applications.
- Support system users that develop smaller, single-threaded applications.
- Automated data pipelines connecting sensors to databases to simulation platforms to enable inflow of real-time observational data from various providers, including NOAA, NASA, USGS, and USACE as well as academic observatories.
- Access research data provided by non-governmental sources, including university and international collaborators.

- Access to the system must be possible by each of the agencies and those sponsored by representative agencies to collaborate on the IHTM initiative without hurdle.
- Follows appropriate rules and regulations to establish required information assurance and security abiding by necessary government regulations.
- Support remote access to the a fully interactive environment without significant communication delay.
- Permit hardware optimization to accommodate different architectures and to push the computational envelope with respect to accelerated systems.

6.2 Making It Happen

To establish a computational testbed facility for IHTM activities, an official testbed development team needs to be formed by agency representatives, charged with developing a charter to outline the goals for establishing the testbed. This interagency team would then initiate a small number of cross-agency communities of practice aimed at achieving the following specific goals: (1) Develop an actionable IHTM governance structure; (2) Develop clear understanding of shared objectives and incentives for collaboration; (3) Develop communication lines to enable interagency collaboration; and (4) Create a system architecture that would enable the establishment of the testbed. Development of joint projects would provide early science benefits to the upfront computational investment requested to develop priorities and phased long-term approaches.

6.2.1 Overcoming Barriers

Integration across multiple agencies and disciplines, each with a shared vision of the IHTM, faces cultural challenges. At present, agencies focus on their individual missions, and how their individual technical and geographic areas of expertise serve those missions. Disciplines are concerned with appropriately addressing how their knowledge is queued into the overall systems model. Even though beneficial capabilities and complementary expertise could be transferred between agencies and disciplinary communities, it is easier to identify barriers to this transfer than to actively pursue it. For example: (1) current momentum and legacy tools may prevent adoption of software engineering best practices; (2) differing cultures and languages hinder collaboration; (3) a gap exists between research and operations; (4) there is perceived competition for limited resources; and (5) existing budgets are allocated to current deliverables and there is no budget to implement changes. The true challenge is to shift away from these excuses and establish vibrant and diverse interagency and multidisciplinary communities that support the development of the IHTM that will enhance both the science and the service to society.

6.2.2 Roadmap for Progress

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (4-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Several existing examples of interagency testbeds should be studied when developing the IHTM testbed. For instance, the Department of Defense (DOD) established several distributed supercomputing facilities under the DOD High-Performance Computing (HPC) program. Multiple DOD groups collaborate effectively on supercomputing applications on the HPC and include partners from non-DOD agencies (e.g. NASA, universities, etc.). NASA has its own collaborative supercomputing facility that is also used by externally sponsored researchers. These systems could either be included and networked as part of the IHTM program or evaluated for their effectiveness as a template for IHTM development.

Near-Term Goals and Activities

- Strategic hire of an interagency person to coordinate and motivate.
- Catalog existing testbeds (e.g., NOAA's Hydrometeorology Testbed [HMT], USACE's Coastal Model Test Bed [CMTB], NASA's Short-term Prediction Research and Transition Center [SPoRT], DOE's International Land Model Benchmarking Project [iLAMB]).
- Consolidate multi-agency data into nationally consistent and open data sets.
- Scope and define common testbed evaluation protocols.
- Understand limitations and opportunities to leverage components.
- Incorporate stakeholder engagement and tools for uncertainty quantification from the start.
- Scope a prototype of a modular testbed framework.
- Develop a design for a prototype testbed capability (e.g., coastal flooding).

Mid-Term Goals and Activities

- Establish prototype testbed, including tools to enable repeatable operations for modeling and data analysis.
- Incorporate scalable workflows that accommodate appropriate levels of complexity and transferability (see Section 1).
- Apply prototype to selected use cases for agency-relevant demonstration, evaluation, and benchmarking.
- Develop community training resources.

Long-Term Goals and Activities

- An effective operational testbed, including tools for ensemble generation and evaluation (stakeholder-informed uncertainty quantification).
- Full-scale integration for coupled numerical and machine-learning approaches.
- A capability to test subsets of models that are agency specific.
- A governance process that allows for testbed maintenance and evolution.

6.3 Benefits to Science and Society

When successful, the IHTM computation testbed will support long-term, barrier-less, institutional collaboration across agencies that creates a new culture, is supported by the agency leadership, is productive and lasting, and more effectively and holistically enables agencies to meet mission objectives. An approach to coordination and governance will be established that enables the co-development of the IHTM software ecosystem, such that the best science and algorithms are integrated without being encumbered by agency boundaries or mission. The scientific teams building these models will be supported in ways that help them ensure that these advances in IHTM serve both the broader community and the missions of collaborating agencies. Mechanisms will be developed to ensure each agency will contribute time, staff, and resources in a way that fairly balances the community (their expertise, and resources) with their mission benefit.

7. Open Science by Design

Addressing the Nation's priority water challenges requires extensive coordination among many federal and state agencies (Figure 13). For example, NOAA, USGS, and USACE coordinate efforts on hurricane predictions, monitoring and emergency response to flooding; several federal and state agencies including the EPA, USGS, NOAA, and USACE participate in the Gulf of Mexico Hypoxia Task Force (https://www.epa.gov/ms-htf/hypoxia-task-force-members); and similarly several agencies including the USDA, EPA, NOAA, USGS, USBR, and DOE are involved in the National Drought Resilience Partnership (https://www.drought.gov/drought/resources/national-drought-resilience-partnership). There are also multiple instances of research co-funding that have occurred to date − for example, the USDA and NSF co-funding of research projects submitted to "Innovations at the Nexus of Food, Energy and Water" (https://www.nsf.gov/pubs/2018/nsf18545/nsf18545.htm; see also previous versions from 2016, 2017); the USDA and NSF co-funding of research projects submitted to Water Sustainability and Climate (http://www.nsf.gov/pubs/2013/nsf13535/nsf13535.htm; see also previous versions from 2010, 2012); and the USDA, DOE, and NSF co-funding of projects submitted to Decadal and Regional Climate Prediction using Earth System Models (https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf12522&org=NSF; see also versions from 2010 and 2013).

Despite several past instances of interagency coordination, integration across multiple agencies faces significant challenges. For example, current momentum and legacy tools may prevent adoption of software engineering best practices; differing cultures and languages hinder collaboration; the gap between research and operations; and competition for limited resources. Even though significant federal and state efforts have been launched to make water data open and interoperable (e.g., Open Water Data Initiative, Consortium of Universities for the Advancement of Hydrologic Science, Inc. [CUAHSI], CA AB155), many challenges remain in being able to seamlessly discover and use data for multiscale modeling efforts. In many instances, data have been collected, but are (1) not accessible for broad use, (2) are in non-standardized formats, (3) lack the metadata to enable integration and use, or (4) are of poor or uncertain quality.

Similarly, a wide diversity of hydro-terrestrial models exists, as developed by different agencies, national laboratories, and individual university researchers for a variety of purposes. This creates the potential for conflict when seeking to develop the best-informed cross-agency approaches to integrated hydro-terrestrial modeling for both management and research.

At present, agencies focus on their individual missions, and how their individual technical and geographic areas of expertise serve those missions. Even though there are beneficial capabilities and expertise that could be transferred between agencies, it is easier to identify barriers to this transfer than to actively address them. The challenge is to overcome these barriers and establish a vibrant and diverse interagency community that supports the development of the IHTM.

A clear need exists for collection of available data for development, calibration, and evaluation of integrated hydrologic terrestrial models across scales from reaction to watersheds to the entire continental U.S. Ideally, data should be easily accessible in standard formats with appropriate metadata and usage policies that enable broad use from scientific analysis to operational forecasting.

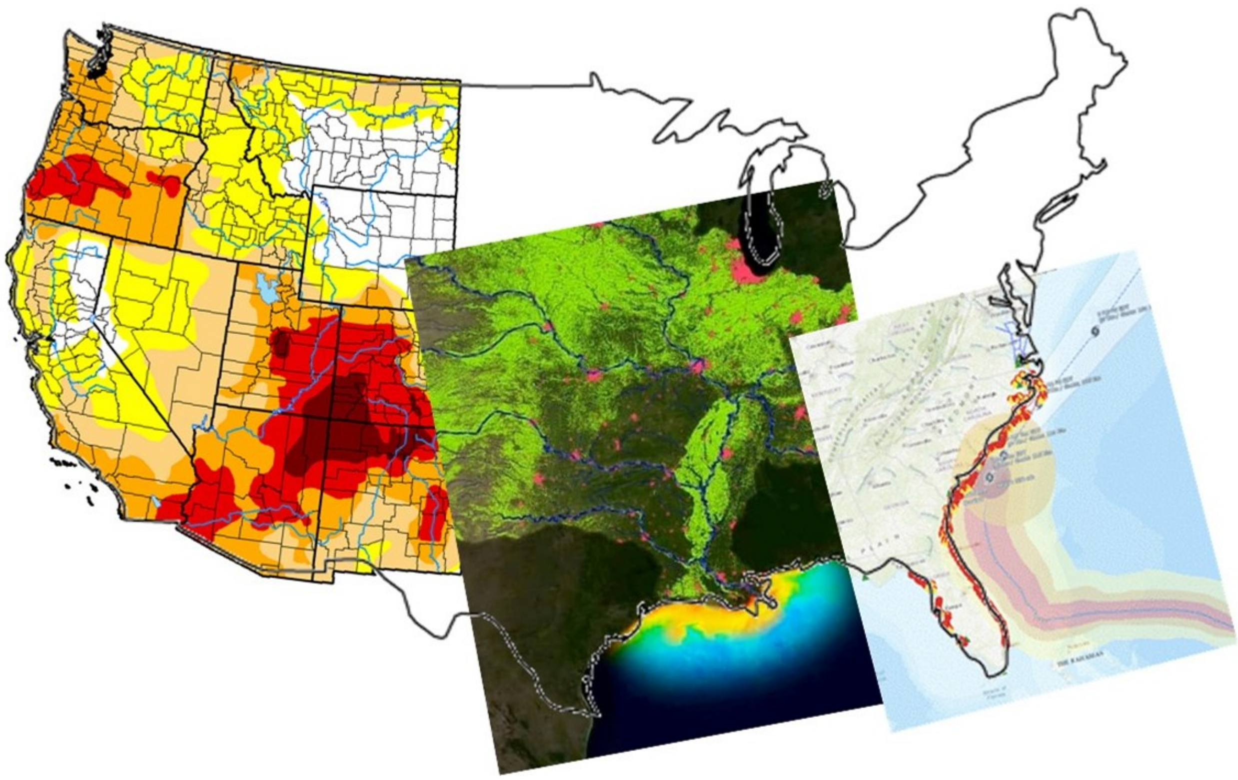

Figure 13. Cross-agency coordination in generating data products and model results are essential to achieving the IHTM vision. Figures from right to left include (a) USGS rapid deployment gauges and other sensors monitoring Hurricane Dorian storm track in September 2019, coordinated with the NOAA National Hurricane Center (b) Map showing nutrient runoff into the Mississippi River leading to the dead zone in the Gulf of Mexico. The extent of the dead zone is forecast by NOAA and used in models run by the interagency Hypoxia Task Force (c) drought conditions in western U.S. provided by the interagency U.S. Drought Monitor. Credits: USGS Flood Event Viewer[1], NOAA[2], U.S. Drought Monitor.[3]

Coordination and support from the top down is required to enable the grass-roots collaboration and integration that will ultimately deliver the IHTM vision. For example, cross-agency efforts are needed to both generate open, reusable, interoperable data sets and to specify standards to which agency codes should conform for interoperability and flexibility, while meeting the needs and objectives of data generators, code developers, and users. Thus, mechanisms must be established to build scientific teams across agencies, laboratories, and universities that will enable the best science and operations; enable seamless integration of science, data, and software; use the best and most knowledgeable people; and use shared resources and equipment. In addition, staffing and financial resources must be contributed from collaborating agencies in an equitable manner, understanding that the benefit to an agency mission is derived from the best IHTM collaboration.

[1] https://www.usgs.gov/media/images/usgs-hurricane-dorian-flood-event-viewer
[2] https://coastalscience.noaa.gov/news/noaa-forecasts-very-large-dead-zone-for-gulf-of-mexico/
[3] https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?West

7.1 IHTM Vision for Open Science by Design

The IHTM vision is the creation of an integrated water community committed to open science by design that collaborates across agencies and academia, identifies common goals, leverages expertise and resources, shares data and research, and co-develops models.

The concept of "Open Science by Design" is to plan research endeavors to be open and collaborative throughout their life cycle − from conception, through study design and data collection, knowledge generation, data analysis and forecasting, through final dissemination and preservation (Figure 14). The vision for open science by design was laid out in a report from the National Academies of Sciences, Engineering, and Medicine (NASEM 2018). Specifically, this report calls out the need for overcoming barriers to sharing research data, methodologies, analyses, and software. Versions of this concept have been promoted by various communities for sharing open data using FAIR principles (Stall et al. 2019, Popkin et al. 2019), and most recently enabling rapid scientific advances towards confronting the coronavirus pandemic (Zastrow 2020). In 2019, DOE convened an interagency workshop on "Open Watersheds by Design" (U.S. DOE 2019) in which the research community jointly explored new approaches for designing watershed science research networks. This workshop represents an initial step toward the concept of an IHTM framework that includes open design of both data and simulation capabilities.

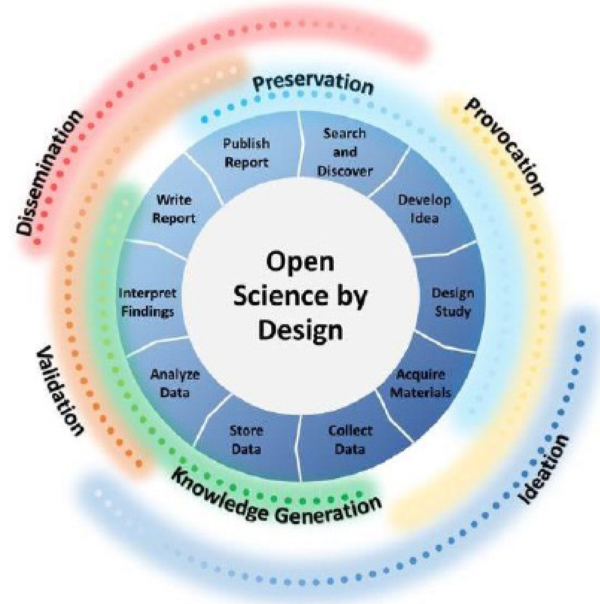

Figure 14. Schematic diagram of the Open Science by Design process (U.S. DOE 2019).

The open science by design mindset is essential for the success of the IHTM effort. Open science by design has the potential to transform scientific research and its pipeline to operations by bringing together agency resources to address grand water-related challenges with greater efficiency and efficacy, and by generating interoperable data and models that will accelerate the creation of actionable knowledge for decision-makers.

7.2 Making It Happen

Workshop participants identified several social and organizational barriers to adopting open science concepts. There was recognition that creating cultural change and aligning agency missions and incentives was a slow but necessary process required to realize the IHTM vision. The participants concurred that initial steps should consist of pragmatic, small efforts that would create early wins to build momentum and establish good working relationships across agency personnel. This would set the stage for achieving mission alignment, creating communities of practice that could work collaboratively on data or model standards, and bringing together resources for funding interagency efforts. In the long-term, this would enable building the IHTM with model co-development, established interagency standards, and a shared mission.

7.2.1 Overcoming Barriers

Current barriers identified were the upfront investments required (time, personnel, budget, and other resources) to share data, co-develop models, and build/maintain collaborations across agencies. This becomes especially hard to justify when such tasks are not explicitly funded or incentivized. In particular, many participants felt that efforts that would lead to more open science are not recognized or rewarded within their organizations, particularly given the mission-oriented nature of federal agencies. This perception of unique, mission-specific needs breeds a build-your-own approach leading to the creation of one-off, custom data products or modeling tools. Additional barriers include the lack of infrastructure or tools to make these tasks easy, and security/privacy concerns for some data sets.

The group identified key needs to overcome current barriers:

- Mission alignment to incentivize collaboration across agency silos
- Identify common needs to minimize redundant activities
- Organizational, financial, and personnel support from agencies to incorporate open science by design
- Pilot successful projects that would build confidence in the vision and show the benefits of engaging in open science by design.

7.2.2 Roadmap for Progress

A concrete plan to create clear incentives and sustained multi-agency support of the communities of practice is vital to IHTM. This includes cooperative research and mission agency funding mechanisms, long-term support for the development and dissemination of evolving open software developments, and coordinated engagements with the broad set of people needed to maintain the rigor and integrity of IHTM software tools. These engagements include training diverse user groups, mechanisms for providing feedback, and innovations in the software development cycle. The workshop participants identified several goals and activities that would help make progress towards the vision of open science by design for the IHTM.

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (3-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Near-Term Goals and Activities

Convene a multi-agency working group with liaisons to generate community buy-in, create incentives, and co-design a pilot project:

- Establish a vision/charter for these collaborative communities supported by agencies, develop a communications plan from that, and begin marketing the process to engage potential collaborators.
- Establish connections with existing relevant organizations (standards bodies, science/professional associations, etc.).
- Establish norms and rules for conduct. These need to apply at several levels (science, management, executive).
- Establish champions as early as possible.
- Identify and organize a suggested set of unifying themes, allowing community members to modify.
- Focus on confidence-building short-term wins. Early work might be established with a Request for Proposals (RFP) process that stresses development of or leveraging collaboration and/or community platform assets for data management.
- Develop IHTM-focused funding, distinct from agency funding for scientific data research, development, and operationalization, to support community facilitation across government, laboratory, and academic communities.

Mid-Term Goals and Activities

Determine and implement common data and model standards through communities of practice:

- Realize forms of mission convergence through development of shared budget initiatives, either in the form of pooling assets or creation of shared new funding programs (like the Great Lakes Restoration Initiative).
- Have a well-established collaboration culture based on enabling policy, infrastructure, and incentivization. Examples of the latter include internal employee recognition for collaborative work and a well-established IHTM-wide RFP process.
- Have agencies communicate with IHTM, outside groups and higher levels of government with a consistent message/voice.

Long-Term Goals and Activities

Transform culture towards sharing data, co-developing models, and generating timely, coordinated forecasts for stakeholders:

- Develop a mature, formalized/standardized process for identification and action on shared mission objectives that is institutionalized within member agencies.
- Exhibit a shared mission through coordinated actions, products, and planning with IHTM member agencies/participants.

- Develop a stable, long-term plan for support of community researchers, facilitators and champions, including salary, training, and travel support, in order to continually evolve the IHTM focus as well as curate previously established (reusable) intellectual assets.

7.3 Benefits to Science and Society

Adopting the "Open Science by Design" vision will enable coordination and governance such that the best science and algorithms can integrated into the IHTM framework without being encumbered by agency boundaries or missions. The science will be greatly improved with more interaction across domains and with stakeholders. This collaborative approach will result in making better predictions with greater efficiency ─ for example, by shifting the energy spent on data and model harmonization to scientific analysis and modeling. Ultimately this will lead to decision-makers having better tools and knowledge, at more relevant spatial scales and temporal resolutions, to take actions that address the huge water-related challenges that the Nation will face over the next few decades. Open and transparent sharing of data and methods will also increase societal trust in science and scientific products.

8. Mission Alignment, Business and Funding Practices

Many federal agencies and federally funded scientists are addressing critical water issues that face the Nation. Although agencies have distinct missions and niches to fill in meeting the Nation's water challenges, all need accurate simulations of the hydrologic cycle and its interaction with society and the terrestrial environment (Figure 15). Currently, agencies, groups within agencies, and individual federally funded scientists routinely develop their own models to meet their management needs. This is practical in that agencies can understand and respond to the specific needs of their stakeholders, but it risks duplication and fragmentation of effort. Given the current complementary efforts of federal agencies and federally funded scientists, the federal hydrologic community is well positioned to leverage its collective capacity to address the Nation's highest-priority water needs, which often span agency missions. To do so will require finding opportunities for interagency collaboration while operating within the agencies' statutorily mandated missions. Our challenge is to mitigate potential fragmentation and leverage synergies to build an IHTM capability in which the whole is greater than the sum of the parts. We can then more effectively advance the individual missions of our agencies and collectively address national priorities.

Figure 15. Word cloud from strategic documents (e.g., mission statements) for the agencies participating in the IHTM workshop.

8.1 IHTM Vision for Mission Alignment and Business and Funding Practices

Many governmental committees and interagency groups advocate for shared needs and ongoing activities related to hydro-terrestrial modeling. However, these groups generally have limited authority to compel agencies and federally funded scientists to adopt a common set of standards or practices. The proposed strategy for the IHTM effort is to focus on compelling use cases that intrinsically require the collective efforts of multiple agencies to advance their individual missions and meet pressing national needs. The opportunity to do together what would otherwise be impossible to do alone will be a powerful impetus to drive sustained development of an IHTM capability for the Nation. Organizing the development of an IHTM capability through technical working groups, focused on a common set of compelling use cases, will promote the development of communities of practice that, if supported and encouraged by their parent organizations/agencies and the Government as a whole, will evolve into self-sustaining entities that establish effective modes of community governance, standards for data and model interoperability, and protocols for model testing and benchmarking.

8.2 Making It Happen

Agency missions range from basic research with a focus on knowledge discovery, to applied research with a focus on solving specific problems, to operational deployment and forecasting in a wide variety of environments. Workshop participants advocated that a next-generation IHTM capability should be designed to bridge the R2O2R development cycle. There is broad recognition that an ecosystem of codes designed to be modular, interoperable, extensible, and scalable would be used by multiple stakeholders and agencies for a variety of purposes extending from basic research to applied problem solving and operational forecasting across a broad range of environments and spatial and temporal scales. To develop a more efficient and robust IHTM national capability, including a practical R2O2R development cycle, systems of governance must be established to define standards for data and model interoperability, thus enabling the natural evolution of the IHTM ecosystem and allowing for improved coordination, collaboration, and competition at increasingly granular scales.

8.2.1 Overcoming Barriers

Although many industries and scientific disciplines have established community standards to enable broad interoperability (e.g., telecommunications industry, world wide web, and to some extent the weather and climate modeling communities), the hydrological community has been less successful at developing coordinated models. Development of robust standards at the community level is often driven by the size of the problem and the lack of resources to develop multiple modeling systems (e.g., global climate models, high-energy physics community, nuclear fusion community, etc.). Community efforts can range from monolithic modeling platforms, with "one-ring to rule them all", to federated approaches consisting of a tapestry of modeling components stitched together via standardized interfaces developed and agreed to by the community. There are certainly tradeoffs between centralized versus distributed model development paradigms and modeling ecosystems. Pre-workshop surveys revealed that most agencies are working internally to develop more modular and interoperable modeling capabilities. Significant discussions have occurred between agencies on how to extend the concepts of interoperable modeling capabilities beyond the agency silos, and to integrate model development activities by federally funded scientists. However, the questions of governance and business and funding models for the development of shared modeling capacity that extends beyond a single agency can be significant obstacles to collaboration and co-development. A theme of the IHTM workshop was that principles of open science by design, if widely adopted by the agencies and communities of practice, could provide a framework for community governance and the collaborative development of an IHTM national capability.

8.2.2 Roadmap for Progress

To better prepare the Nation to deal with its many and growing water challenges, agencies will need to evolve their business and funding practices and mission alignment to support the collaborative development of IHTM capabilities and communities of practice, which would also advance individual agency missions and overall scientific capacity. In the near term, this will require participating agencies to have a stake in the results for early wins and pilot projects that use flexible approaches and leverage available resources. In the mid-term, more explicit interagency coordination is needed to optimize mission alignment and business and funding practices. In the long term, structural adjustments within and between agencies will be required and additional resources will be needed for optimal impact and sustainability.

Goals and activities were defined by workshop participants for the near term (0-3 years), mid-term (3-6 years), and long term (7-10 years). They are provided here as bulleted lists specific to this element of the ITHM; additional details are available in the summary logic models produced from workshop materials (Appendix 3). An overall IHTM roadmap with more comprehensive discussion is provided in Chapter 1.

Near-Term Goals and Activities

- Learn from innovative business and funding practices of previously successful, best-in-class interagency collaborations.
- Identify and adapt flexible mechanisms within agency business and funding practices to pilot early collaborations and successes. Leverage incentives that motivate the research community, forge interagency connections, and advance R2O2R developments.
  - Build a strategic plan and interagency roadmap for a long-term sustainable commitment to IHTM. Share (at a minimum) and coordinate (ideally) budget requests and mission goals to achieve mission alignment.
  - Build/leverage incentives and reward structure for individuals and agencies.
- Create (or leverage existing) community of practice working groups.
  - Fund dedicated liaisons to working groups.
- Build prototypes through multilateral engagements based on specific use cases.
- Enable dedicated agency liaisons to working groups.
- Define what each agency needs from IHTM and how they would use the envisioned capability to advance their missions. From these analyses, agencies can contribute to the development of IHTM design requirements.
- Build prototypes through multilateral engagements based on specific use cases.

Mid-Term Goals and Activities

- Build sustainable communities of practice.
- Define components of a five-year strategic plan.
- Explore and identify non-traditional funding sources − new processes needed for nimble public-private partnerships.
- Establish flexibility to be responsive to both top-down and bottom-up opportunities.
- Identify and communicate benefits along the entire R2O2R pathway.
- Build a “better mousetrap” − applied use of research for societal benefit; use societal needs to define research needs.

- Provide funding for new research opportunities.
- Establish mechanisms to ensure long-term sustainability of communities of practice:
  - Demonstrate benefits of use-case prototypes along the entire R2O2R pathway.
  - Reduce overhead for data management.
- Provide dedicated and sustainable funding mechanisms for new research opportunities:
  - Establish processes for creating non-traditional funding sources through nimble public-private partnerships and new interagency funding opportunities.
  - Respond to both top-down and bottom-up opportunities.
- Demonstrate success in the applied use of IHTM research for societal benefit.

Long-Term Goals and Activities

- Coordinate budget requests and mission goals to achieve mission alignment.
- Develop a sustainable governance strategy.

8.3 Benefits to Science and Society

The long-term goal of IHTM is for agencies to become better aligned and to creatively work through effective business and funding practices, thereby enabling IHTM collaborations and partnerships that advance agency-specific missions and meet the needs of their stakeholders and the Nation. The benefits to science and society include:

- Effective stewardship and efficient use of federal resources
- Seamless interagency capabilities
- Transparency and clarity in traversing the federal landscape for capabilities (the public) and resourcing (the science community)
- Vastly improved leveraging of the Nation's science assets through an R2O2R framing, enabled by mission alignment and improved business and funding practices
- A nation better prepared to deal with its many and growing water challenges, threats, and uncertainties.

9. A Roadmap for Integrated Hydro-Terrestrial Modeling

Capitalizing on the interests, enthusiasm, ideas, and commitment to action expressed by the participants of the "Integrated Hydro-terrestrial Modeling (IHTM) Workshop", there followed considerable discussion on how to synthesize the results and develop a set of "path forward" ideas for both near-term action as well as sustained development and long-term collaboration. Notably, there was significant support for "jump-starting" the process with a focus on near-term actions designed to engage various groupings of the community in a range of collaborative activities both on topics aligned with the three major water challenges – (1) Nutrient loading, hypoxia, and harmful algal blooms; (2) Water availability in the western U.S.; and (3) Extreme-weather-related water hazards − as well as foundational IHTM methodology development that aligns with the full range of IHTM mission responsibilities of the various agencies, from basic and applied research to operations and the full scope of R2O2R. Characteristics and shared goals of agencies that are early contributors to development of an IHTM capability include:

- the **shared motivations** emerging from the workshop that are serving to catalyze interests in moving the community forward
- **targets of opportunity** aligned with the Priority Water Challenges, including candidate use cases
- a set of foundational IHTM **technical and methodological advances**
- a set of potential **organizational, structural, and cultural alignments** that can underpin a high-functioning interagency community of practice
- a candidate set of **potential near-term actions and early results** that can begin now and deliver impactful early results
- gauges and metrics of IHTM community success through the development and application of **success indicators**.

9.1 Shared Motivations

Collectively, four overarching themes were repeatedly identified and cited throughout the workshop as motivations for a more dedicated interagency IHTM capability. Many of these are described elsewhere throughout the report and are merely summarized and collectively cited here.

1. **Inform solutions to the Nation's critical hydro-terrestrial challenges**. The three priority water challenges ([1] Nutrient loading, hypoxia, and harmful algal blooms; [2] Water availability in the western U.S.; and [3] Extreme-weather-related water hazards) were strongly embraced by the Water Subcabinet and by agencies participating in the workshop. Additionally, and in preparation for discussions at the workshop, agencies submitted candidate use cases aligned with the three priority water challenges. These water challenges span agency mission boundaries and encompass a broad range of geographies, complex system dynamics and feedbacks, and critical processes spanning hydrological, climatic, and biophysical systems as well as land-use/land-cover, agricultural, built infrastructure, and societal, economic, and decisional environments. Independent of these three specific priority water challenges, there was shared interest in developing IHTM capabilities and tools that would respond to significant societal challenges, not just for individual topics or geographies, but extensible to a range of potential applications and stakeholders.

2. **Increase leverage and cross-agency impacts from collective investments in IHTM**. Through interagency cooperation, the opportunity to deliver added and cross-disciplinary benefits to individual agency missions was seen as a potential major benefit. Sharing of data, models, codes, and methods, as well as more generally filling individual agency gaps in these areas and others, were widely seen as efforts in which all agencies benefit. Additionally, and capitalizing on unique agency capabilities and strengths, new and more integrated capabilities were recognized to be high-value outcomes, providing greatly enhanced societal benefit within available IHTM resources.
3. **Strengthen the R202R connections and accelerate the timeframe from innovation to benefits**. A repeated theme throughout the workshop emphasized strengthening connections and accelerating exchanges along the innovation pipeline. More specifically, creating stronger ties between the basic research, applied research, and operations communities (R2O2R) was deemed essential for substantive progress to be made within agency missions and in IHTM. Opening presentations from representatives of these three communities set the stage and reinforced this underlying motivation for the workshop and the many specific benefits and expected outcomes from related activities. Importantly, user feedback to the research community was seen as particularly important in helping to frame use-inspired dimensions for research planning, whether basic research, applied research, or both.
4. **Overcome technical and institutional barriers to development and applications**. A significant part of the workshop focused on technical and institutional barriers and specific actions to overcome those barriers, also described in more detail in separate chapters of this report and summarized below in sections 9.3.2 and 9.3.3.

9.2 Targets of Opportunity

The priority water challenges identified for this workshop are not mutually exclusive. The complexity of the challenges and the understanding necessary to enable management decision-making and to identify options necessitates the inclusion of multiple human, physical, and biological processes that are common across the spectrum of the three priority water challenges. Parameterizing a suite of processes for one challenge will significantly advance the understanding and use within other water challenge contexts. Furthermore, developing a capability to understand and scale processes across the relevant time and space scales will enable specific solutions to general problems. Because of the breadth, complexity, and interrelationship of the priority water challenges, it will be important to identify target areas of opportunity where substantive near-term progress can be made, particularly when that progress advances understanding in more than one water challenge.

Hypoxia, Excess Nutrients, and Harmful Algal Blooms

Development of near-term forecasts for events such as water quality exceedances or levels of concern and testing of surrogates other than nutrient concentrations are needed that can improve probabilistic forecasts and the likelihood of conditions such as hypoxia events or HABs. Initially, less emphasis is expected on modeling the detailed system processes and more on improving the accuracy and utility of forecasts. In specific areas with a history of problems with hypoxia and HABs, there may already be well-developed indicators that predict the next season's extent and severity of hypoxia but the transfer value of those methods to other regions/systems has generally been limited.

In the long term, models need to address scenario projections under changing future conditions. These models will require specific process representation and integration of physical-biological-human drivers. In particular, the current models do not adequately capture the full range of physical transport processes for nutrient exports from source areas or the range of possible human-controlled processes.

Predictive models are needed that can simulate the distribution, transport, and reaction of nutrients through the hydrologic components (Gomez-Velez et al. 2015) and related physical and biological processes that influence the likelihood of hypoxia and HAB events (Garcia et al. 2016). Models must be able to represent influences of changing hydroclimatic conditions and other natural and societal drivers such as changing land cover, land use, natural and anthropogenic sources of constituents, and effects of specific land-use practices on transport and reaction.

Water Availability in the Western U.S.

The challenges regarding water availability in the western U.S. result not only from water scarcity, but also from (often competing) human management of natural and engineered systems that span a range of spatial and temporal scales. In the near term, and with water being over-allocated among users, and water storage and conveyance practices that may lead to losses through increased evaporation and leakages, it is critical to better monitor, understand, and represent the engineered and natural system processes toward more efficient/effective management practices. Specific needs include:

1. The availability of observations for initial conditions, data assimilation, and evaluation with more relevant observations and faster access.
2. Improved accuracy of hydro-meteorological forecasts (snow, atmospheric rivers, monsoon).
3. Improved understanding of normal and alternative sectoral operations, such as aquifer recharge and overall surface water-groundwater interactions.
4. Improved understanding of uncertainty, variability and predictability of the natural system in response to changing climate.

For longer-term development, there are various underlying assumptions about how water availability will be stressed by climate, water use, and management practices. It is critical to better understand individual processes and how they interact as well as the underlying assumptions across institutions about how water availability will be stressed by climate, water use, and management practices to inform policy and adaptation strategies. It is also critical to make multi-sectoral observations available to better evaluate integrated analysis approaches. For all decision-making time horizons, there is also a need to coordinate observation networks, data sets, modeling tools, and assumptions across agencies and institutions with the goal of more robust and transparent cross-institutional decision-making.

Water-Related Hazards

The science underlying flood response and water resource management is complex and spans mission boundaries. Given a changing climate and uncertain hydrologic and human response, we need far-field projections of future hydrologic events along with related impacts. A comprehensive framework is required to analyze the frequency, distribution, and intensity of extreme weather and hydrologic events, and the resulting impacts on inundation, infrastructure, water supply, and water quality. An Integrated Hydro-Terrestrial Modeling (IHTM) approach is needed to conduct process studies and simulations, assimilate real-time information, and provide medium- and long-term forecasts that can be used by decision-makers to help address imminent challenges.

Specifically, IHTM technical needs will require collaborative, community approaches to address:

1. Data silos within and across institutions, as well as data isolation from computing resources.
2. Fragmentation, gaps, and lack of interoperability for component and partially aggregated modeling systems.
3. Monolithic codebases resulting in duplicative investments in algorithm development.
4. Weaknesses in uncertainty quantification and lack of conveyance to end-user communities.
5. Weak or missing hydrologic and land surface process representations, as well as inadequate process coupling in some critical focus areas.
6. Mismatches in spatial and temporal scales between atmospheric, water, and land process representations that result in undue computational burdens and/or lost precision.

Beyond these technical needs, other needs arise from (and must address): (1) the lack of life-cycle management perspectives in models and modeling systems, that is, R2O2R connections; (2) tradeoffs in modeling details and complexity for accuracy and precision when confronted by oftentimes compressed decision-making timelines; (3) the costs of rapid cycling and iterations for research-to-operations assimilation; (4) uncertainties about agency capabilities, sometimes overlapping, and the unique contexts that drive them; and (5) observed institutional biases for legacy systems and their associated inertia.

Use Cases

To further motivate and direct development of a national IHTM capability, workshop participants identified exemplary integrated use cases within the three Priority Water Challenges that cannot be fully addressed without leveraging complementary and synergistic capabilities across multiple agencies. A preliminary set of use cases was submitted through the various agencies, some targeting specific (local) Priority Water Challenges and some addressing more than one Priority Water Challenge. **In total, 52 interagency IHTM use cases were submitted.** (See Appendix D). Submissions are aligned as reflected in the following table.

Table 2. Agency use cases as aligned with Priority Water Challenges.

POTENTIAL AGENCY INTEREST IN PRIORITY WATER CHALLENGES AS REFLECTED BY USE CASE SUBMISSIONS
Hypoxia, Nutrients, and Harmful Algal Blooms USDA, EPA, USGS, NOAA, USBR, USACE, DOE, NSF
Water Availability in the Western U.S. USGS, DOE, USBR, USDA, USACE, EPA, NSF
Water-Related Hazards NOAA, USACE, USGS, USBR, DOE, NSF

Considerably broader interest was raised, and ideas better merged and formulated, through the many workshop discussions, with greater details summarized in the individual chapters of this workshop report.

The submitted use cases are organized by title for each Priority Water Challenge below. Those that align with more than one challenge are listed multiple times. Each use case submitted provides the following specific information: 1) challenge, 2) context, 3) specific enhancements, 4) impacts and benefits, 5) potential stakeholders, 6) potential users, 7) potential developers, 8) scientific and technical challenges, 9) opportunity for IHTM development, 10) phased approach, and 11) points of contact.

Table 3. Candidate use cases by Priority Water Challenge.

Candidate Interagency Use Cases by Priority Water Challenge

Flooding and Extreme Weather-Related Water Hazards

1. Integration of Coastal and Hydrologic Models
2. Urban Flooding
3. Flooding During Extreme Events
4. Springtime Ice Jam Flooding in the Northeast
5. Natural / Virgin Flows
6. Modeling Complex Groundwater Surface Water Interactions
7. Incorporate Channel Transmission Losses into the WRF Hydrologic Model to Improve Estimate of Recharge, Water Availability, and flood peaks in Arid &Water Availability in the West Semiarid Environments
8. International Basins
9. Management Representation in Water Resource Planning and Assessment Models
10. Integration of National Water Model (NWM) and Hydrologic and Water Quality System (HAWQS)
11. Forecasting Impacts of Disturbance Events in the Rocky Mountain west
12. Aging Dam and Levee Infrastructure and Dam Breach Analysis
13. Use-Case for the Delaware River Basin
14. Delaware Bay: groundwater salinization and ground subsidence
15. Flooding for Mid-Atlantic Coastal Localities
16. Precise Near-Realtime Urban Flood Detection and Prediction (FloodAware)
17. Use-Case for Lake Champlain-Richelieu River Flood Forecasting
18. Compound flooding in Miami-Dade county
19. Linked longitudinal (instream) and lateral (groundwater) flows in regulated river corridors
20. Use-Case for Lower Ohio-Mississippi River Flood Control
21. Frozen ground affected flooding in glacial landscapes
22. POST-WILDFIRE IMPACTS TO FLOOD RISK MANAGEMENT (FRM): LASCONCHAS WILDFIRE-NEW MEXICO
23. Hurricane Irma, Florida, 2018
24. Use-Case for Great Lakes Water Level Forecasting and Management
25. Multi-Objective IHTM Modeling: Non-Climate Factors

Hypoxia, Nutrients, and Harmful Algal Blooms

1. Sediment/Nutrient Transport in the Mississippi
2. Integration of watershed hydrology, reservoir water quality, and operations
3. Integration of watershed hydrology, reservoir water quality, and operations
4. Nutrient Loading in the Mississippi Basin
5. Management Representation in Water Resource Planning and Assessment Models
6. Aging Dam and Levee Infrastructure and Dam Breach Analysis
7. Use-Case for the Delaware River Basin
8. Delaware Bay: groundwater salinization and ground subsidence
9. Use-Case for Lake Erie Hypoxia
10. Use-Case for Lake Erie Nutrient Loadings
11. Use-Case for Lake Erie Harmful Algal Blooms
12. Use-Case for the Upper Mississippi River Basin and Eastern Corn Belt
13. Use-Case for the Central Mississippi River Basin
14. Nutrients and Gulf of Mexico Hypoxia
15. Nutrients, Harmful Algal Blooms, and Toxic Algae
16. Integration of Surface and Subsurface Hydrologic and Hydraulic Models
17. Gunnison River Basin Use Case
18. Linked longitudinal (instream) and lateral (groundwater) flows in regulated river corridors
19. Integration of National Water Model (NWM) and Hydrologic and Water Quality System (HAWQS)
20. Mississippi River Basin water quality (N) modeling with river corridor exchanges
21. Carbon cycling by river corridors of the CONUS
22. Fully coupled modeling of river corridors (i.e., including riparian, parafluvial, and hyporheic zones)
23. Assessing surface-groundwater flows in regulated rivers using component-based models
24. In- and Near-Field Modeling and Data Needs for Effective Nutrient Management
25. International Basins
26. Multi-Objective IHTM Modeling: Non-Climate Factors

Water Availability in the West

1. Water Resource Allocations and Planning
2. Multi-Objective IHTM Modeling: Non-Climate Factors
3. Western U.S. water management for multi sector analyses
4. San Juan watershed - management for multi sector analyses
5. Groundwater Banking in the Western U.S.
6. Natural / Virgin Flows
7. Modeling Complex Groundwater Surface Water Interactions
8. International Basins
9. Integration of watershed hydrology, reservoir water quality, and operation
10. Management Representation in Water Resource Planning and Assessment Models
11. Snow Modeling and Forecasting for the State of California
12. Fully coupled modeling of river corridors (i.e., including riparian, para-fluvial, and hyporheic zones)
13. Gunnison River Basin Use Case
14. Incorporate Channel Transmission Losses into the WRF Hydrologic Model to Improve Estimate of Recharge, Water Availability, and flood peaks in Arid & Semiarid Environments
15. Aging Dam and Levee Infrastructure and Dam Breach Analysis
16. Linked longitudinal (instream) and lateral (groundwater) flows in regulated river corridors
17. Land Stewardship Use Case: A solution to "go-back" land—restoring abandoned farmland and sustaining rural communities
18. Hydro-Economic Resilience & Western Water Stress (FEWSION
19. Water Sustainability for Managed Watershed Systems: Columbia River Basin Use
20. Assessing surface-groundwater flows in regulated rivers using component-based models
21. Meeting Future Water Needs to Accommodate Western Population Growth
22. Groundwater depletion as a coupled human and natural system

Advancing integrated use cases, workshop participants envisioned a future in which agencies are better aligned and creatively working together on shared scientific, technical, and analytic challenges; foundational IHTM methodological needs; and efficient business and funding practices, collectively "leaning-in" on functional community of practice. The intended result would be IHTM collaborations and partnerships that simultaneously advance the individual missions of water-related agencies while enhancing the degree and extent to which the agencies could respond to the needs of their stakeholder and user communities, and importantly, the water challenges of the Nation. A critical initial step identified at the workshop advocated for multiple agencies to invest resources (leveraging existing research and capabilities) in pilot projects designed around integrated use cases, using flexible and collaborative approaches. Such integrated use cases would not only provide rallying points for initial development and testing of an IHTM capability and build on existing interagency collaborations, but would also spur new governance concepts, data standards, and model interoperability solutions required for a national IHTM capability. It was a widely held view that participating agencies having a stake in the results could and would lead to some early successes as well as building the foundations for a sustained, longer-term effort.

Technical and Methodological Advances

The workshop also provided an opportunity for scientists from multiple agencies to share and document various organizational, cultural, financial and technical obstacles that must be overcome to achieve a new and national IHTM capability. The technical challenges and opportunities for enhanced integration of capabilities were discussed at length.

9.2.1 Organizational, Structural, and Cultural Alignments

Key organizational and cultural challenges discussed included how to best align different missions of water-related agencies to address common problems; how to minimize duplication of effort within and across agencies; how to develop reward systems that acknowledge the value of data, information, and code sharing; how to share resources across agencies and leverage existing activities to meet common objectives; and the development of a culture of interagency cooperation and, most importantly, open science.

Workshop participants recognized that to support effective and efficient interagency collaboration, new *governance approaches and business models* are required that overcome current organizational barriers. Although it is recognized that multiple agencies share water responsibilities, their distinct business and funding practices and current alignments may not fully support solutions to complex shared problems such as the Priority Water Challenges.

9.3 Potential Near-Term Actions and Early Results

One of the more significant undercurrents of the workshop emerged around opportunities to jump-start progress with actions that could deliver high impact with early results. **Importantly, engagements at the workshop facilitated a broad range of bilateral, trilateral, and multilateral plans for subsequent meetings across agencies based on common interests. Many of the plans oriented around the Priority Water Challenges and particular use-case topics within all three of the Priority Water Challenges. However, there were wide-ranging discussions and plans being made for follow-up to address foundational technical challenges as well as cross-agency institutional challenges, both of which are summarized above**.

Below are examples extracted from the workshop sessions and conversations that serve as candidates for potential early actions. These “early win” pilot projects are centered on Priority Water Challenges implemented by multiagency teams (two lead agencies plus others in support capacity) that build confidence in the vision and show the benefits of coordinated data and modeling infrastructure through IHTM.

- **Pilot projects and/or use-case groups (conceivably one or more in each of the Priority Water Challenges organized around unique topics).**
  - Each group establishes charter and identifies key R2O2R partners and stakeholders (must engage local and regional stakeholders in development).
  - Led by interested agencies but with defined opportunities and intentionality for other agencies to engage and come onboard.
- **Establish a community of practice oriented around technical working groups, shared capabilities, and improved communications and coordination.**
  - Build enterprise capacity to support interoperable data and model infrastructures.
  - Convene interagency technical working groups with liaisons embedded within Priority Water Challenge pilot project groups as well as across each technical working group to guide and execute opportunities for interoperable data and codes, generate community buy-in, create incentives, and co-design a pilot project implemented around technical groups and/or computational testbeds.
  - Organize joint principal investigator workshops and community webinars.
  - Initiate early work (potentially) with an RFP process that stresses development or leveraging of collaboration and/or community platform assets for data management.
  - Determine and implement common data and model standards with the goal of developing a mature, formalized/standardized process for data management and interoperable code development.
  - Establish immediately a vision/charter for these collaborative communities supported by agencies; develop communications plan from that charter, and begin a marketing process to engage potential collaborators, including key R2O2R partners and stakeholders.
  - Establish connections with existing relevant organizations (standards bodies, science/professional associations, etc.).
  - Establish norms and rules for conduct. These need to apply at several levels (science, management, executive).
  - Establish champions as early as possible.
  - Identify and organize a suggested set of unifying themes, allowing community members to modify.
  - Develop (even a small amount of) funding to support community facilitation, distinct from funding for scientific data research, development, and operationalization.

Although focused a bit more on long-term, sustainable efforts, items below could be initiated now, with potentially early interim results but likely long-term outcomes.

- **Establish regular venue/meeting for agency leads to share progress on Priority Water Challenges pilot projects and technical working groups and to identify next steps for further integration.**

- **Develop a coordinated interagency funding model for IHTM.**
  - Establish shared budget initiatives or new shared funding programs.
  - Identify and adapt flexible funding mechanisms within current agency business and funding practices to pilot early collaborations and successes.
  - Discover existing investments at different agencies through a listening tour.
  - Define each agency's needs from IHTM and how they would use the envisioned capability to advance their missions. From these analyses, agencies can contribute to the development of IHTM design requirements.
  - Leverage incentives to motivate coordinated research.
  - Build prototypes through multilateral engagements based on specific use cases.
- **Develop stable, long-term mechanisms that support community facilitators and champions, including salary, training, and travel support, in order to continually evolve the IHTM focus as well as curate previously established (reusable) intellectual assets.**
- **Establish new metrics for success and incentives that motivate interagency collaboration and adoption of open science by design principles that underpin IHTM.**
- **Establish a plan, strategy, and mechanism to support an active and productive R2O2R operation that advances science and missions.**

9.4 Indicators of Success

While a specific set of *success metrics* was not developed and vetted as part of this workshop, it was a topic of conversation in the various sessions and was included on many of the discussion templates. The various chapters of this report include sections on outcomes, expected benefits to science and society, or both. From these sections, it should be possible to extract and produce a set of quantitative and qualitative metrics that can be used by the community to gauge its progress and adapt and learn as efforts unfold. The subsequent development and application of success metrics is another near-term, actionable item that is both important and worthy of separate mention here, if the IHTM community of practice is to become efficient, productive, societally relevant, and high performing over time.

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Appendix A: Workshop Agenda

Integrated Hydro-Terrestrial Modeling: Development of a National Capability

4-6 September 2019
Hosted at the National Science Foundation
2415 Eisenhower Avenue, Alexandria VA 22314

PLENARY IN BLACK; BREAKOUTS IN RED, See separate Breakout room#/topic schedule

DAY 1 – September 4, 2019

8:30-8:50 AM Welcome

Welcome from NSF – William Easterling, NSF (10 min)
Welcome from Interagency Steering Committee – Diana Bauer, DOE (5 min)
Welcome from Workshop Co-Chairs (5 min)

8:50-9:45 Introduction/Motivation

Integrated Hydro-Terrestrial Modeling (IHTM): Overview and Framing – David Lesmes, USGS (15 min)
Perspectives on IHTM Development: The Research-to-Operations-to-Research (R2O2R) Cycle (30 min)

- **Operations and Decision Support** – Edward Clark, NOAA (10 min)
- **Applied Research** – Christa Peters-Lidard, NASA (10 min)
- **Basic Research** – Bob Vallario, DOE (10 min)

IHTM: Vision for the Future – Tim Scheibe, Co-Chair, PNNL (10 min)

9:45 – 10:00 Keynote Address

Dr. Timothy Petty (Department of Interior, Assistant Secretary for Water and Science)

10:00 – 10:15 Break

10:15 – 10:50 Workshop Vision, Structure, and Outcomes (Plenary Room)

Workshop structure, format, and agenda – Harry Jenter, Co-Chair, USGS (10 min)
Expectations for outputs, next steps, and eventual outcomes – Efi Foufoula-Georgiou, Co-Chair, UC Irvine (10 min)
Group discussion (15 min)

Breakout #1: Priority Water Challenges

10:50 – 11:30 Breakout #1: Framing Presentations and Overview (Plenary Room)

Moderator: Harry Jenter, Co-Chair, USGS

- **Hypoxia, Nutrient Loading, and Harmful Algal Blooms –** Scot Hagerthey, EPA (10 min)
- **Western Water Availability –** Bridget Scanlon, UT Austin (10 min)
- **Flooding and Extreme-Weather Related Water Hazards–** Jane Smith, USACE (10 min)

Discussion/Questions

11:30 – 11:50 Charge to Breakouts – Tim Scheibe (PNNL), David Moulton (LANL)

11:50 – 12:00 Grab lunch and head to your breakout session …

12:00 – 2:30 Priority Water Challenge Breakouts

Breakout Session 1 Hypoxia, Nutrient Loading, and Harmful Algal Blooms**:** Near-Term Prediction
Breakout Session 2 Hypoxia, Nutrient Loading, and Harmful Algal Blooms: Long-Term Projection
Breakout Session 3 Western Water Availability: Near-Term Prediction
Breakout Session 4 Western Water Availability: Long-Term Projection

Breakout Session 5 Flooding and Extreme-Weather Related Water Hazards: Near-Term Prediction
Breakout Session 6 Flooding and Extreme-Weather Related Water Hazards: Long-Term Projection

2:30 – 2:45 Break

2:45 – 3:15 Breakout #1 Report Outs (Plenary Room)
Moderator: Harry Jenter, Co-Chair, USGS
5 min and 2 slides for each breakout. Just present Long-Term Goals and Outcomes for Science and Society
Breakout Session 1 Hypoxia, Nutrient Loading, and Harmful Algal Blooms**:** Near-Term Prediction
Breakout Session 2 Hypoxia, Nutrient Loading, and Harmful Algal Blooms: Long-Term Projection
Breakout Session 3 Western Water Availability: Near-Term Prediction
Breakout Session 4 Western Water Availability: Long-Term Projection
Breakout Session 5 Flooding and Extreme-Weather Related Water Hazards: Near-Term Prediction
Breakout Session 6 Flooding and Extreme-Weather Related Water Hazards: Long-Term Projection

Breakout #2: Carpenters and Shepherds - Building and Maintaining Community Capacity for IHTM

3:15 – 3:55 Breakout #2 Framing Presentations and Overview (Plenary Room)
Moderator: Efi Foufoula-Georgiou, Co-Chair, UC Irvine

- **Data management and Community Platforms and Standards** – Jordan Read, USGS (10 min)
- **Software Engineering - Interoperability and Sustainability/Improvement**- Joe Hughes, USGS (10 min)
- **Cross-Disciplinary Workflows, Analysis and Evaluation (UQ)** – Jennifer Rice, PNNL (10 min)
- **Building Computational/Modeling Testbeds:** Brian Cosgrove, NOAA (10 min)

3:55 – 4:05 Charge to Breakouts – Tim Scheibe (PNNL), David Moulton (LANL)

4:05 – 5:30 Breakout #2: Building and Maintaining Community Capacity for IHTM – Session I
Breakout Session 1: Data management and Community Platforms and Standards
Breakout Session 2: Software Engineering for Interoperability and Sustainability/Improvement
Breakout Session 3: Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Near-Term Prediction
Breakout Session 4: Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Long-Term Projection
Breakout Session 5: Building Computational/Modeling Testbeds: Requirements for Near-Term Prediction
Breakout Session 6: Building Computational/Modeling Testbeds: Requirements for Long-Term Projection

5:30 Adjourn

Day 2 - September 5, 2019

8:30 – 10:00 Breakout #2: Building and Maintaining Community Capacity for IHTM – Session II
Continue discussions in breakout groups from Session I

10:00 – 10:15 Break

10:15 – 10:45 Breakout #2 Report Outs (Plenary Room)
Moderator: Efi Foufoula-Georgiou, Co-Chair, UC Irvine
5 min and 2 slides for each breakout. Present Long-Term Goals and Outcomes for Science and Society

Breakout Session 1: Data management and Community Platforms and Standards
Breakout Session 2: Software Engineering for Interoperability and Sustainability/Improvement
Breakout Session 3: Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Near-Term Prediction
Breakout Session 4: Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Long-Term Projection
Breakout Session 5: Building Computational/Modeling Testbeds: Requirements for Near-Term Prediction
Breakout Session 6: Building Computational/Modeling Testbeds: Requirements for Long-Term Projection

Breakout #3: Organizational Challenges: Building a Sustainable IHTM Community

10:45 - 11:15 Breakout #3 Framing Presentations and Overview (Plenary Room)
Moderator: Tim Scheibe, Co-Chair, PNNL

- **Open Science by Design – Data, Codes, and Interoperability** – Charuleka Varadharajan (10 min)
- **Open Science by Design – Building Communities of Practice** – Michael Fienen and Patrick Reed (10 min)
- **Integrated Modeling – New Way of Doing Business** – David Moulton (10 min)

11:15 – 11:25 Charge to Breakouts – David Moulton (PNNL)

11:25 ***Lunch available … to be taken to breakout***
11:35 – 2:15 Breakout #3: Organizational Challenges and Building a Sustainable IHTM Community
Breakout Session 1: Open Science by Design – Data availability, integration, and interoperability
Breakout Session 2: Open Science by Design – Standardization vs Flexibility
Breakout Session 3: Open Science by Design – Community Development and Outreach
Breakout Session 4: Business and Funding Models
Breakout Session 5: Mission Alignment with IHTM
Breakout Session 6: Interagency Coordination and Governance

2:15 – 2:30 Break

2:30 – 3:00 Organizational Challenges Report Outs (Plenary Room)
Moderator: Tim Scheibe, Co-Chair, PNNL
5 min and 2 slides for each breakout. Just present Long-Term Goals and Outcomes for Science and Society
Breakout Session 1: Open Science by Design – Data availability, integration, and interoperability
Breakout Session 2: Open Science by Design – Standardization vs Flexibility
Breakout Session 3: Open Science by Design – Community Development and Outreach
Breakout Session 4: Business and Funding Models
Breakout Session 5: Mission Alignment with IHTM
Breakout Session 6: Interagency Coordination and Governance

Breakout #4: Synthesizing an IHTM Vision and Next Steps

3:00 – 4:00 Next Steps Panel and Moderated Discussion (Plenary Room)
4:00 – 4:15 Charge to Breakouts – David Lesmes

4:15 – 5:30 Final Breakout: Synthesizing an IHTM Vision – Session I
Breakout Session 1: Water Challenges - Hypoxia, Nutrient Loading, and Harmful Algal Blooms
Breakout Session 2: Water Challenges - Water Availability in the West
Breakout Session 3: Water Challenges - Flooding and Extreme Weather-related Water Hazards
Breakout Session 4: Technical Challenges - Data Management and Community Platforms

Breakout Session 5: Technical Challenges - Software Engineering for Interoperability
Breakout Session 6: Technical Challenges - Cross-Disciplinary Workflows, Analysis and Evaluation (UQ)
Breakout Session 7: Technical Challenges - Building Computational/Modeling Testbeds
Breakout Session 8: Organizational Challenges - Open Science by Design: Data, Codes, and Community Development
Breakout Session 9: Organizational Challenges – Mission alignment, Interagency Coordination, and Business Models

5:30 Adjourn

DAY 3 - September 6, 2019

8:30 – 9:30 Final Breakout: Synthesizing an IHTM Vision – Session II
Continue discussions in breakout groups from Session I

9:30 – 9:45 Break

IHTM Vision for the Future and Next Steps (Plenary Room)

9:45 – 9:55 Introduction to Workshop Outcomes – David Lesmes, USGS
9:55 – 10:25 Out-Briefs: Outcomes on Priority Water Challenges

- Hypoxia, Nutrient Loading, and Harmful Algal Blooms (10 min)
- Water Availability in the West (10 min)
- Flooding and Extreme Weather-related Water Hazards (10 min)

10:25 – 11:05 Out-Briefs: Outcomes on Building and Maintaining Community Capacity

- Data Management and Community Platforms (10 min)
- Software Engineering for Interoperability (10 min)
- Cross-Disciplinary Workflows, Analysis, and Evaluation (10 min)
- Building Computational/Modeling Testbeds (10 min)

11:05 – 11:25 Out-Briefs: Outcomes on Organizational Challenges to Building an IHTM

- Open Science by Design: Data, Codes, and Community Development (10 min)
- Interagency Coordination, Convergence, and Business Models (10 min)

11:25 – 11:30 Next Steps: Top 10 List
11:30 – 12:30 Panel Discussion: Reflections on Building a National IHTM Capacity
Moderators: Tom Torgersen (NSF), Bob Vallario (DOE)
Dr. Marlen Eve (USDA, Deputy Administrator Agricultural Research Service)
Dr. Scott Borg (NSF, Deputy Assistant Director for Geosciences)
Dr. Don Cline (USGS, Associate Director of Water Resources Mission Area)
Dr. Edward Clark (NOAA, Deputy Director of Office of Water Prediction)
Dr. Tristram West (DOE, Senior Technical Advisor, Office of Biological and Environmental Research)
Mr. Thomas Wall (EPA, Director, Watershed Restoration, Assessment, and Protection Division)
Dr. Jane M. Smith (USACE, Senior Research Scientist, Engineer Research and Development Center)
Dr. Jack Kaye (NASA, Associate Director for Research, Science Mission Directorate)

12:30 Adjourn

1:00 – 4:00 Writing Team Begin Writing Workshop Report

Breakout Session Rooms

Integrated Hydro-Terrestrial Modeling: Development of a National Capability

4-6 September 2019

Hosted at the National Science Foundation

Breakout #1 … grab lunch and head to your breakout session…

Priority Water Challenges 1150-230pm WEDS

1. Hypoxia, Nutrient Loading, and Harmful Algal Blooms:Near-Term Prediction Rm 3150
2. Hypoxia, Nutrient Loading, and Harmful Algal Blooms:Long-Term Projection Rm 3160
3. Western Water Availability: Near-Term Prediction Rm 3170
4. Western Water Availability: Long-Term Projection Rm 3180
5. Flooding and Extreme-Weather Related Water Hazards:Near-Term Prediction Rm 3190
6. Flooding and Extreme-Weather Related Water Hazards:Long-Term Projection Rm 3110

Breakout #2

Carpenters and Shepherds: Building and Maintaining Community Capacity for IHTM

Session I 4:10 – 5:30 Weds

1. Data management and Community Platforms and Standards Rm 3150
2. Software Engineering for Interoperability and Sustainability/Improvement Rm 3160
3. Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Near-Term Prediction Rm 3170
4. Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Long-Term Projection Rm 3180
5. Building Computational/Modeling Testbeds: Requirements for Near-Term Prediction Rm 3190
6. Building Computational/Modeling Testbeds: Requirements for Long-Term Projection Rm 3110

Breakout #2 continues

Session 2 8:30 – 10:00 Thurs

1. Data management and Community Platforms and Standards Rm 3150
2. Software Engineering for Interoperability and Sustainability/Improvement Rm 3160
3. Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Near-Term Prediction Rm 3170
4. Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) for Long-Term Projection Rm 3180
5. Building Computational/Modeling Testbeds: Requirements for Near-Term Prediction Rm 3190
6. Building Computational/Modeling Testbeds: Requirements for Long-Term Projection Rm 3110

Breakout #3

Organizational Challenges and Building a Sustainable IHTM Community

Session 1 Thurs 11:30 – 2:15 ***Lunch available … to be taken to breakout***

1. Open Science by Design – Data availability, integration, and interoperability Rm 3150
2. Open Science by Design – Standardization vs Flexibility Rm 3160
3. Open Science by Design – Community Development and Outreach Rm 3170
4. Business and Funding Models Rm 3180
5. Mission Alignment with IHTM Rm 3190

6. Interagency Coordination and Governance Rm 3110

Breakout #4: Synthesizing an IHTM Vision and Next Steps
Session #1 415 – 530pm Thurs

1. Water Challenges - Hypoxia, Nutrient Loading, and Harmful Algal Blooms Rm 3150
2. Water Challenges - Water Availability in the West Rm 3160
3. Water Challenges - Flooding and Extreme Weather-related Water Hazards Rm 3170
4. Technical Challenges - Data Management and Community Platforms Rm 3180
5. Technical Challenges - Software Engineering for Interoperability Rm 3190
6. Technical Challenges - Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) Rm 3110
7. Technical Challenges - Building Computational/Modeling Testbeds Rm 3210
8. Organizational Challenges - Open Science by Design: Data, Codes, and Community Rm 3220
9. Organizational Challenges – Interagency Coordination and Business Models Rm 3430

Breakout #4: Synthesizing an IHTM Vision and Next Steps …continues
Session #2 830-930am Fri

1. Water Challenges - Hypoxia, Nutrient Loading, and Harmful Algal Blooms Rm 3150
2. Water Challenges - Water Availability in the West Rm 3160
3. Water Challenges - Flooding and Extreme Weather-related Water Hazards Rm 3170
4. Technical Challenges - Data Management and Community Platforms Rm 3180
5. Technical Challenges - Software Engineering for Interoperability Rm 3190
6. Technical Challenges - Cross-Disciplinary Workflows, Analysis and Evaluation (UQ) Rm 3110
7. Technical Challenges - Building Computational/Modeling Testbeds Rm 3210
8. Organizational Challenges - Open Science by Design: Data, Codes, and Community Rm 3220
9. Organizational Challenges – Interagency Coordination and Business Models Rm 3430

Appendix B: Participants

Integrated Hydro-Terrestrial Modeling: Development of a National Capability
4-6 September 2019
Hosted at the National Science Foundation

Interagency Executive Planning Team:
David Lesmes, U.S. Geological Survey
Bob Vallario, U.S. Department of Energy
Tom Torgersen, National Science Foundation

Workshop Lead Coordinator:
Jessica Moerman, U.S. Department of Energy

Workshop Co-Chairs:
Tim Scheibe, Pacific Northwest National Laboratory
Efi Foufoula-Georgiou, University of California Irvine
Harry Jenter, U.S. Geological Survey

Workshop Attendees

John Bolten	*National Aeronautics and Space Administration, GSFC*
Carlos Del Castillo	*National Aeronautics and Space Administration, GSFC*
Brad Doorn	*National Aeronautics and Space Administration*
Jared Entin	*National Aeronautics and Space Administration*
Jack Kaye	*National Aeronautics and Space Administration*
Sujay Kumar	*National Aeronautics and Space Administration, GSFC*
Randal Koster	*National Aeronautics and Space Administration, GSFC*
Christine Lee	*National Aeronautics and Space Administration, JPL*
Forrest Melton	*National Aeronautics and Space Administration, AMES*
Christa Peters-Lidard	*National Aeronautics and Space Administration, GSFC*
Frederick Policelli	*National Aeronautics and Space Administration, GSFC*
Patrick Burke	*National Oceanic and Atmospheric Administration, National Ocean Service*
Edward Clark	*National Oceanic and Atmospheric Administration, National Weather Service*
Brian Cosgrove	*National Oceanic and Atmospheric Administration, National Weather Service*
Jesse Feyen	*National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab*
Trey Flowers	*National Oceanic and Atmospheric Administration, National Weather Service*
Nels Frazier	*National Oceanic and Atmospheric Administration, National Weather Service*
Tom Graziano	*National Oceanic and Atmospheric Administration, National Weather Service*
Debbie Lee	*National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab*
David Mattern	*National Oceanic and Atmospheric Administration, National Weather Service*
Fred Ogden	*National Oceanic and Atmospheric Administration, National Weather Service*
David Gochis	*National Center for Atmospheric Research*
Tim Schneider	*National Center for Atmospheric Research*
Andy Wood	*National Center for Atmospheric Research*

Jerad Bales	*National Science Foundation, CUAHSI*
Scott Borg	*National Science Foundation*
William Easterling	*National Science Foundation*
Laura Lautz	*National Science Foundation*
Ingrid Padilla	*National Science Foundation*
Lina Patino	*National Science Foundation*
Thomas Torgersen	*National Science Foundation*
Bayani Cardenas	*University of Texas - Austin*
Laura Condon	*University of Arizona*
Efi Foufoula-Georgiou	*University of California - Irvine*
Carl Hershner	*Virginia Institute Marine Sciences*
David Hyndman	*Michigan State University*
Ilena Irwin	*Ohio State University*
Praveen Kumar	*University of Illinois at Urbana-Champaign*
Reed Maxwell	*Colorado School of Mines*
Patrick Reed	*Cornell University*
Ying Reinfelder	*Rutgers University*
Ben Ruddell	*Northern Arizona University*
Bridgette Scanlon	*University of Texas - Austin*
Raghavan Srinivasan	*Texas A&M University*
David Tarboton	*Utah State University*
Greg Tucker	*Univeristy of Colorado – Boulder*
Paul Ullrich	*University of California - Davis*
Thomas Wahl	*University of Central Florida*
Jeffrey Arnold	*U.S. Army Corps of Engineers, Climate Change Program*
Michael Deegan	*U.S. Army Corps of Engineers, Institute for Water Resources*
Charles Downer	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
John Eylander	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
Shawn Komlos	*U.S. Army Corps of Engineers, Institute for Water Resources*
Guillermo Mendoza	*U.S. Army Corps of Engineers, Institute for Water Resources*
Jodi Ryder	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
Jane Smith	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
Mark Wahl	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
Charles Wiggins	*U.S. Army Corps of Engineers, Engineer Research and Development Center*
Lindsay Bearup	*U.S. Bureau of Reclamation, Research and Development Office*
Daniel Broman	*U.S. Bureau of Reclamation, Research and Development Office*
Kenneth Nowak	*U.S. Bureau of Reclamation, Research and Development Office*
David Blodgett	*U.S. Geological Survey, Water Resources Mission Area*
Nathaniel Booth	*U.S. Geological Survey, Water Resources Mission Area*
Donald Cline	*U.S. Geological Survey, Water Resources Mission Area*
William Cunningham	*U.S. Geological Survey, Water Resources Mission Area*
Jessica Driscoll	*U.S. Geological Survey, Water Resources Mission Area*
Mike Fienan	*U.S. Geological Survey, Water Resources Mission Area*
Jud Harvey	*U.S. Geological Survey, Water Resources Mission Area*
Joe Hughes	*U.S. Geological Survey, Water Resources Mission Area*
Harry Jenter	*U.S. Geological Survey, Water Resources Mission Area*
Tim Kern	*U.S. Geological Survey, Water Resources Mission Area*

David Lesmes	*U.S. Geological Survey, Water Resources Mission Area*
Timothy Quinn	*U.S. Geological Survey, Water Resources Mission Area*
Jordan Read	*U.S. Geological Survey, Water Resources Mission Area*
Kendra Russell	*U.S. Geological Survey, Water Resources Mission Area*
Katie Skalak	*U.S. Geological Survey, Water Resources Mission Area*
Roland Viger	*U.S. Geological Survey, Water Resources Mission Area*
Jeff Arnold	*U.S. Department of Agriculture, Agricultural Research Service*
Ron Bingner	*U.S. Department of Agriculture, Agricultural Research Service*
Nancy Cavallaro	*U.S. Department of Agriculture, National Institute of Food and Agriculture*
Richard Derksen	*U.S. Department of Agriculture, Office of the Chief Economist*
James Dobrowolski	*U.S. Department of Agriculture, National Institute of Food and Agriculture*
Emile Elias	*U.S. Department of Agriculture, Agricultural Research Service*
Marlen Eve	*U.S. Department of Agriculture, Agricultural Research Service*
David Goodrich	*U.S. Department of Agriculture, Agricultural Research Service*
Martin Locke	*U.S. Department of Agriculture, Agricultural Research Service*
Daniel Marks	*U.S. Department of Agriculture, Agricultural Research Service*
Glenn Moglen	*U.S. Department of Agriculture, Agricultural Research Service*
John Sadler	*U.S. Department of Agriculture, Agricultural Research Service*
Steven Thomson	*U.S. Department of Agriculture, National Institute of Food and Agriculture*
Teferi Tsegaye	*U.S. Department of Agriculture, Agricultural Research Service*
Marca Weinberg	*U.S. Department of Agriculture, Economic Research Service*
Diana Bauer	*U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy*
Paul Bayer	*U.S. Department of Energy, Office of Science*
Gerald Geenaert	*U.S. Department of Energy, Office of Science*
Justin Hnilo	*U.S. Department of Energy, Office of Science*
Renu Joseph	*U.S. Department of Energy, Office of Science*
Jessica Moerman	*U.S. Department of Energy, Office of Science*
Robert Vallario	*U.S. Department of Energy, Office of Science*
Tristram West	*U.S. Department of Energy, Office of Science*
Xingyuan Chen	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Ethan Coon	*U.S. Department of Energy, Oak Ridge National Laboratory*
Mohamad Hejazi	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Jordan Macknick	*U.S. Department of Energy, National Renewable Energy Laboratory*
David Moulton	*U.S. Department of Energy, Los Alamos National Laboratory*
Scott Painter	*U.S. Department of Energy, Oak Ridge National Laboratory*
Jennie Rice	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Joel Rowland	*U.S. Department of Energy, Los Alamos National Laboratory*
Tim Scheibe	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Carl Steefel	*U.S. Department of Energy, Lawrence Berkeley National Laboratory*
Charu Varadharajan	*U.S. Department of Energy, Lawrence Berkeley National Laboratory*
Chris Vernon	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Nathalie Voisin	*U.S. Department of Energy, Pacific Northwest National Laboratory*
Jalal Mapar	*U.S. Department of Homeland Security*
Aubrey Bettencourt	*U.S. Department of the Interior, Office of Water and Science*
Timothy Petty	*U.S. Department of the Interior, Office of Water and Science*

Jennifer Shinen	*U.S. Department of State*
Joel Corona	*U.S. Environmental Protection Agency, Office of Water*
Mike Cyterski	*U.S. Environmental Protection Agency, Office of Research and Development*
Todd Doley	*U.S. Environmental Protection Agency, Office of Water*
Scot Hagerthey	*U.S. Environmental Protection Agency, Office of Research and Development*
John M Johnston	*U.S. Environmental Protection Agency, Office of Research and Development*
Stephen Muela	*U.S. Environmental Protection Agency, Office of Water (ORISE)*
Rajbir Parmar	*U.S. Environmental Protection Agency, Office of Research and Development*
Brenda Rashleigh	*U.S. Environmental Protection Agency, Office of Research and Development*
Taimur Shaikh	*U.S. Environmental Protection Agency, Region 6*
Michelle Thawley	*U.S. Environmental Protection Agency, Office of Water*
Michael Trombley	*U.S. Environmental Protection Agency, Office of Water*
Steve Whitlock	*U.S. Environmental Protection Agency, Office of Water*
Kurt Wolfe	*U.S. Environmental Protection Agency, Office of Research and Development*
Tom Wall	*U.S. Environmental Protection Agency, Office of Water*
Dwane Young	*U.S. Environmental Protection Agency, Office of Water*
Jennifer Saleem-Arrigo	*U.S. Global Change Research Program*

Appendix C: Logic Models

During the course of the workshop, three thematic breakout sessions were conducted with the following themes:

1. Priority Water Challenges
2. Building and Maintaining Community Capacity for IHTM
3. Organizational Challenges and Building a Sustainable IHTM Community

In each session, the workshop participants were divided into six groups, each assigned a different topic within the overall theme of that breakout session. Each breakout group participated in a facilitated exercise to generate ideas, which were then formulated into logic models. A logic model is a tabular depiction of the relationships among the current state, intended outcomes, resources, and intermediate goals. The logic model captures the steps needed to achieve the long-term vision given the current status and available resources.

This appendix presents the 18 summary logic models (3 themes x 6 topics each theme) generated by the workshop participants. These outcomes are incorporated at a high level into the main body of this report; this appendix provides the full logic models for completeness of detail.

Logic Model for Breakout 1.1: HABs, Hypoxia, Nutrient Loading Requirements for Near-Term (< 1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Harmful Algal Blooms (HABs) problems are widespread, data is fragmented among agencies. There is a lack of data coordination and process understanding of links between nutrient loading, HABs, and other physical and biological factors. Heavy investments in measurements and application of empirical techniques have paid off by helping to produce useful forecasts of HABs in specific places with long term (> 10-yr) data sets. However, those pilot study successes are not transferable. Key words are Reactive/Responsive, Disjointed, “Claims”, and Specific/Non-transferable	Increased funding and mandate for collaboration and standardization. Bring together scientific staff dispersed across agencies and relevant fields using historical data. Based on lessons learned, improve future data collection and modeling approaches. Increase funding and mandate for collaboration and standardization.	New levels of interactions among agencies and researchers with complementary skills and mission. Emphasis on data integration and building of FAIR databases. Build the network and define a multi-scaled approach. For areas with enough data, attempt to build transferable binary predictor models first, e.g., models that predict Y/N for coming year. Also work on selecting and developing most appropriate existing water quality (WQ) models for HABs prediction, and work on developing HABs monitoring that will permit forecasting at many places. Will need data-sharing agreements with baseline determinations, standards data gap analysis facilitated by a communications campaign.	Build and calibrate next-generation models that are validated against data. Also, must educate public about potential for science to contribute to powerful solutions. Refine models to estimate HABs probabilities based on real-time, cumulative data using accessible application. Also need to improve data infrastructure. Start linking models across landscapes and aquatic systems from freshwater to estuaries. Required are strong inter-governmental relationships (one creative idea: talent-recruiting partnerships among agencies).	Integration of hydrologic, biological, and social models, with emphasis on decision-support tools. Models produce 7-10-day forecasting of HABs with uncertainty in needed areas. Ultimate goal would be defined by a national water model w/integrated WQ prediction that could be adapted to predict HABs outbreaks anywhere in real time. That level of success, for many reasons, could be unrealistic; however, such a model would provide a starting point to refine models wherever blooms are becoming a problem. Key words supporting success are “Common platforms” and “Standardization” to make all products maximally useful across national/regional/state/local scales.	To advance understanding of HABs we must advance understanding of causes. Success will measurably decrease risks to human health and health of aquatic ecosystems and will support economic growth. The path forward makes use of a new generation of models, featuring hybrid models that are physics-based but take advantage of capabilities of artificial intelligence and machine learning. The results bring about improved understanding of biological and physical controls on water quality. Improvements take shape in multiple dimensions of human health, better ecosystem services, and economic benefits. Success is built on greater focus and coordination among agencies to leverage funding and resources. A participatory environment revolutionizes how science serves society – “Amazon for HABs”.

Logic Model for Breakout 1.2: HABs, Hypoxia, Nutrient Loading Requirements for Long-Term (> 1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Empirical models cannot address changing future conditions. Requires process representation and integration of physical-biological-human drivers to be useful for scenario projections. In particular, the current models do not adequately capture the full range of physical processes for nutrient exports from source areas. Beyond the physical-biological drivers that are a challenge to model, there are, for example, the externalities of human behavior such as policy, market choice, and producer decisions are generally not considered. Integrated modeling of HABs, hypoxia, and nutrient loading is a significant challenge. There is limited representation in existing models of terrestrial processes linking biological (plant, microbes, fungi) and physical (soil structure, soil chemistry, moisture dynamics, etc.) and how processes interact across scales (plot to field to watersheds to regions) as well as the terrestrial aquatic linkages to be represented.	Existing models can be initially improved through use of better synthesized data. Co-production of priorities across agencies, academics, and stakeholders is key to fast progress. Integrated surface/subsurface hydrologic transport models should be as complex in process representation as needed, but no more! Successful models will show consistency with experimental, observational, and theoretical approaches. Interagency and academic cooperation at priority field sites, e.g., DOE Science Focus Areas, USGS NGWOS, Critical Zone Observatories, Long Term Ecological Research, etc., should be supported.	Key beginnings are in data standardization, integration of existing physical, biological models in ways that are useful for understanding and prediction from plot to field to watershed scales. Early applications should be planned to identify data gaps, validate models with data, estimate uncertainty, and build and test prototypes of linked models.	Develop interoperability of disciplinary models to integrate physical, biological, and social models. Seek integrated modeling approaches that are transferable and scalable from watershed to regional scales. Evaluate strengths and build hybrid models that bring together strengths of physically based models with statistical models for transferable applications. Scope for eventual applications anywhere in U.S. but test multi-scale value by focusing on validation at priority sites.	Emphasize decision support, multi-scale representation of processes, coupled human-natural system models for co-evolutionary dynamics of human actions and socio-economic factors and natural system dynamics. Evolve models that produce practical products and tools for prediction everywhere.	Models that provide better understanding of "optimal" strategies for nutrient management, especially feedbacks, synchronicities, couplings, and non-linear behaviors. More reliable explanatory and predictive models for nutrient export from source regions, and, more informed decision/policy making approaches that encourage use of scientific information in long-term planning. Interagency and academic cooperation will support the focus needed to accomplish predictive modeling of sources and variability of nutrients across scales in space and time, with, ability to develop informed decision-making across space and time scales with actionable outcomes that can help stakeholders reduce hypoxia. An important key to success is modeling that directly consider nutrient/economics tradeoffs with a means to simplify outcomes in ways that directly lessen threats to human health and ecosystem functions.

<table>
<tr><th colspan="6">Logic Model for Breakout 1.3: Western Water Availability
Requirements for Near-Term (< 1 year) Prediction</th></tr>
<tr><th>2</th><th>3</th><th>6</th><th>5</th><th>4</th><th>1</th></tr>
<tr><th>Current Situation</th><th>Inputs/Resources</th><th>Near-Term Goals
(1-3 years)</th><th>Mid-Term Goals
(4-6 years)</th><th>Long-Term Goals
(7-10 years)</th><th>Outcomes (impacts on science and society)</th></tr>
<tr>
<td>Driven by specific science questions and applications, there is considerable knowledge of regional water availability drivers (physical and human – engineered and governance) within each agency/community. Yet those drivers influencing water availability are not consistently represented within models across different research and operational user communities. Many modeling approaches focus on a specific spatial or temporal scale, region and drivers, with complex representations of natural systems but simplified representation of human systems, or vice versa. The development of integrated models and supporting observation data sets are also not necessarily coordinated.</td>
<td>Mission-specific water availability research programs at government agencies: NASA observation network, USGS monitoring and groundwater modeling, DOE integrated research programs, USBR prediction and allocation, USACE predication and safety operations, NOAA modeling and forecasting, USDA demand prediction, etc.

University research that encourages multidisciplinary collaborations and collaboration with individual government agencies.</td>
<td>1) Defragmenting data

Improve monitoring network (more uses, identify long-term needs).

Data standardization for multi-sectoral analyses.

Local/state representations to address spatial variability in water management, allocation, and regulatory process.

Map sectoral water demand, withdrawals, and consumptive uses.

Fully characterize fluxes (supply and demand).

2) Collaborative modeling

Catalog modeling approaches with mission-specific underlying assumptions and representations.

Collaboration on observation networks, data assimilation, and model development to support the near-term prediction of water availability that will support the understanding and accurate prediction of co-evolving/managed water-dependent physical and engineered systems in IHTMs.

Improve seasonal prediction and increase the horizon toward addressing more uses, consistently.</td>
<td>Coordination with long-term projection activities for water availability, including conjunctive surface and groundwater management, quality, and use, to better represent the adaptability of systems and support the development of long-term resilient hydro-terrestrial systems.</td>
<td>End-to-end modeling framework for multi-sectoral applications with uncertainty quantification (UQ).

National data steward – water information commons, adaptive remote-sensing information.</td>
<td>Improvements take shape in multiple dimensions of water security, food security, and energy security.

Success is built on greater focus and coordination among agencies to leverage funding and resources. A participatory environment revolutionizes how science serves society.

A community-wide integrated understanding and quantification of near-term natural and managed water availability drivers (e.g., physical, governance, operations) for a range of applications (agriculture, energy, transport, etc.).

Better prediction leading to safety, food security, economic growth.

Public trust – better use of products and funding.

Resilience of water systems.</td>
</tr>
</table>

Logic Model for Breakout 1.4: Western Water Availability Requirements for Long-Term (> 1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Siloed purpose-built models lacking interoperability and extensibility. Data gaps, multiple and overlapping models that are difficult to compare, disconnects between data and models. Decisions made based on uncertain, incomplete, and unvalidated data. Heavy reliance on stationary assumptions and past conditions.	Federal data sets, federal research/funding, academic research, existing models, computing resources.	Findable and open data and model repositories. Inventory of models. Framework to support interoperable model components for specific applications. Build on our currently working prototypes.	Interoperable model components and common data/model standards adopted. Stakeholder management. Enhanced multi-agency funding. Cross-scale observation technologies. Benchmarking of integrated models.	A framework that is open, interoperable, and linked to data. An open community model that is stakeholder driven and includes comprehensive uncertainty analysis. Unified modeling architectures	**Science:** A framework to connect disciplines, agency missions and to improve predictions and water availability. Better understanding of water resources and human interactions. Reproducible open-source modeling tools that are scalable. **Society:** More reliable water supply prediction and better decision-making. Enhance water sustainability for economic, environmental, and social uses.

Logic Model for Breakout 1.5: Extremes-Related Water Hazards Requirements for Near-term (< 1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Asynchronous modeling systems at various scales and resolutions. Goal: decision support for high-impact hydrology. Limited, actionable flood intelligence. Incomplete physical process representations. Limited interoperability. High cost for research and transition to operations. High degree of uncertainty. Fragmented information sources. Poor connections/siloed data with relevant models.	Available: observational networks (limited); geographic information systems (GIS) foundational data; Existing modeling systems; Forcing Needed: funds/resources; requirements documentation; shared development environment; data standards; common APIs, libraries; enhanced observational networks; enhanced initial states in models. Water data sets, land cover, and sediment. Process understanding. Code standardization. Broadly accepted program interfaces (APIs). Data provided by multiple agencies. Models provided by multiple agencies.	Community standards. Inundation mapping tools for rapid refresh. Improved observational networks. Establish governance. Develop/adopt code and data standards. Model process development. Interoperability framework. More complete data sources. More available data.	Archive of inundation maps plus observations and model results. Community consensus on uncertainty quantification methods. Inundation products integrated with demographic, economic, infrastructure for risk assessment. Assess, assess, assess. High Performance Computing (HPC) access improvement (cloud). Testbed and evaluation. Incentivization to adopt standards. Better understanding of physical processes.	System enhancements to address sediment budgeting and management. Water-quality monitoring and forecasting and water security, etc. for social decision support in a common operating picture. Community investment (training, informed scientific understanding). Actionable water intelligence (local to national). More sophisticated data sources. Answering more challenging and complex questions.	Strengthens reproducibility and consistency across models. Advances in data science, computational efficiency, and model synchronization. Interoperability speeds time to operations (applications) and research. Cross-domain data and capabilities are enhanced. Exploration of complex uncertainty propagation. Save lives and protect property. Minimize disruptions and facilitate commerce. Enhanced decision support tools and information for safety, economy and resiliency. A well-informed, event-ready public.

Logic Model for Breakout 1.6: Extremes-Related Water Hazards Requirements for Long-Term (> 1 year) Prediction					
2	3	6	5	4	1
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Silo approach to mission-oriented forecast capabilities. limited process linkages. Insufficient data. Inadequate uncertainty assessment. Poorly understood tipping points. Fragmented, diffuse, disconnected, and proprietary modeling and data systems across agencies. Science increasingly problematic. Rudimentary global models. Detailed local modeling driven with down-scaled climate model outputs. Agency-specific models. Data gaps and missing processes. Absence of central governance. Currently fragmented activities. Capabilities that are aligned.	Expanded data acquisition, analysis, synthesis. Enhanced model interoperability. Interagency collaboration and cooperation. Improved/linked ecological and societal models. Agency-specific capabilities related to weather/climate modeling, hydrology, modeling, numerical methods, and understanding the built infrastructure environment/capacity. Existing models, data sets, disconnected data management systems. Supercomputing capacity. CUAHSI and emerging capabilities. Existing models. Observational and framework data. Multi-agency investment. Physical models. Socio-economic research. Stakeholder engagement. Federal and non-federal data. Agency missions.	Data sharing. Identify future scenarios. Communities of practice. Community data platforms. Open source. Test beds. Establish governance. Establish decision context. Establish requirements. Establish long-term records. Understand existing capabilities across community. Radically improve data availability. Better and more extensive stakeholder engagement.	Uncertainty quantification. Model interoperability. Improved model fidelity and resolution (where needed). Interoperable software. Community workflows. Testing and evaluation of modeling systems. Advanced techniques for remote sensing and modeling. Pattern recognition. Establish data and model credibility. Understand how to account for random disturbances. Avoid over-calibration of models. Identify possible roles for AI. Implementation framework for integration of components. Open source.	Identify tipping points and range of possible outcomes. Functional forecast capability. Better water policy. Computationally driven AI. Fully integrated and interoperable modeling frameworks. AI to understand unknown unknowns. Understand how to characterize 50+ year planning horizon. Account for physical processes over-decadal and longer time scales. Ability to run and evaluate complex meaningful scenarios at appropriate scales. Sustained innovation. Fully incorporated socio-economic and geopolitical considerations. Improved physical understanding. Available and accessible to all.	Multi-disciplinary integration of information and cross-agency and community collaboration. Improved understanding of the physical processes that contribute to an integrated hydrologic-terrestrial prediction system, and the complexity that governs the interactions, feedbacks, and overall dynamics. Improvement of skill of long-term/lead modeling capabilities. Improvements in understandings of feedbacks and controls. Integrating water, energy, carbon, and nutrient cycling under global change. Creation of trans-disciplinary integrative information and approaches. IHTM assessment capability for extreme flood risk driven by socio-economic and climate trends. Availability of more powerful predictive tools for long-range planning and development spanning a broad range of systems, sectors, and user communities. Improved water security, safety, economic conditions, health, and resource management and decisions. Reduced damages and losses. Improved decision-making and risk management. A more harmonious, resilient, secure society.

Logic Model for Breakout 1.6: Extremes-Related Water Hazards Requirements for Long-term (> 1 year) Prediction (CONTINUED)					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Responses to single agencies, stakeholders, disciplines. Limited data. Limited stakeholder engagement. Unsustainable approaches vulnerable to catastrophe and unanticipated impacts. Science and information focus on physical systems.			Data support for model development and testing. Create a nexus approach. Enable improved modeling of extremes. improved risk/benefit assessment.		

Logic Model for Breakout 2.1: Data Management and Community Platforms and Standards					
2	3	6	5	4	1
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Communities and platforms exist with varying degrees of formalization. Connections between these communities are generally weak. Programmatic support for development of communities and community platforms is generally lacking, although there are a few "bright spot" examples. This collection of communities has produced or provided access to a variety of useful ideas, methods, and tools, but overall organization of these offerings is not strong and are not always clearly identified as part of best practice workflows or as supported by policy. Capture and reuse of ideas could be made much stronger. In terms of data standards, the breakout team felt there are no widely used standards for hydrodynamic, hydrologic, or hydrographic data in models. In some cases, relevant standards do not exist. Standards for hydrometric data (e.g., stream gauging) were found to be lacking in particular.	Champions were identified as being critical for raising awareness of existing and potential collaborative communities and tools, and to help make community-based collaboration more culturally mainstream within members' home agencies. Engagement of domain scientists was called out as an important input. Aggressive recruitment and substantial involvement from a diversity of members was identified as being important for these communities to be vital and representative of the range of type of work that the IHTM concept hopes to realize. This refers to staff of different personal backgrounds, levels of experience, and subject-matter expertise, but also refers to at least three classes of staff: 1) practitioners/researchers/developers, 2) project managers, and 3) agency executives and other upper-level managers. In addition to these human resources, Executive-level support of agencies participating in IHTM is needed: To make clear to staff how internal programs and projects align with IHTM communities. To incentivize and otherwise motivate staff participation in a highly collaborative way that might be a new work experience or culture. To provision technical assets to support community collaboration, including shared data storage and compute facilities and collaboration/communication platforms (such as Confluence or github). All of these flow from funding support with a clear rationale for their allocation, along with supporting policy and guidance for work plan development.	Establish vision/charter for these collaborative communities supported by agencies immediately, develop communications plan from that, and begin marketing process to engage potential collaborators. Establish connections with existing relevant organizations (standards bodies, science/professional associations, etc). Establish norms and rules for conduct. These need to apply at a number of levels (science, management, executive). Establish champions as early as possible. Identify and organize suggested set of unifying themes, allowing community members to modify. Focus on confidence-building short term wins. Early work might be established with an RFP process that stresses development or leveraging collaboration and/or community platform assets. Develop even a small amount of funding to support community facilitation, distinct from	Publish initial round of IHTM community-based standards and best management practices. Fund and promote these through outreach/training to drive adoption. Continue to fund testing and evolution of standards. Realize forms of mission convergence through development of shared budget initiatives, either in the form of pooling of assets or creation of shared new funding programs (like the Great Lakes Restoration Initiative). Have a well-established collaboration culture based on enabling policy, infrastructure and incentivization. Examples of the latter include internal employee recognition for collaborative work and a well-established IHTM-wide RFP process. Agencies participating in IHTM interact with outside groups and higher levels of government with a	Develop mature, formalized/standardized process for identification and acting on shared mission objectives that is institutionalized within member agencies. Exhibit shared mission through coordinated actions, products, and planning that IHTM member agencies/participants. Have a stable, long-term plan for support of community facilitators and champions, including salary, training, and travel support, in order to continually evolve IHTM focus as well as curate previously established (reusable) intellectual assets. Have a well-organized set of community platforms or a unified/converged platform for IHTM collaboration. Develop standards for hydrography, hydrodynamics, and hydrologic modeling that are incorporated in those of broader organizations, for example within the Open Geospatial Consortium WaterML2 specification. Member agencies routine share and reuse models and data created through the IHTM communities to fulfill their missions.	Development of a robust set of collaborative communities around IHTM, based on shared social scientific platforms, agency culture, and shared standards and tools, will fundamentally accelerate the process of improving scientific knowledge and the capacity to apply it to real-world, societally pressing natural resource questions. This will be achieved by actively building on the current standards, best practices, and technologies. Impact on the scientific community will be realized by greatly enhanced discovery and reuse of scientific knowledge (data, methods, tools), development of new knowledge, and more efficient and appropriate use of those assets. At a higher level, the IHTM community will improve its ability to communicate many kinds of information through robust collaboration platform(s). The current level of effort associated with sharing and reusing hydro-

Logic Model for Breakout 2.1: Data Management and Community Platforms and Standards (CONTINUED)					
2	**2**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
		funding for scientific research, development, and operationalization. Establish funding for community-based standards development and adoption to address IHTM needs. Community should produce a roadmap for IHTM standards and data management. Participating agencies should commit to adopting/implementing these standards. Sponsorship of an IHTM “user conference” to bring together domain (i.e., earth) and computer scientists.	consistent message/voice. Develop thinking for transition from initial crop of focused work groups, shared data, tools, and infrastructure, and best management practices into standard operating procedures for IHTM community. Well-developed and supported content and team for outreach and training. First generation of shared technical infrastructure (data storage, compute capacity, catalogs) will be in wide use. General adoption of user-centered design principles.		terrestrial and other forms of earth science knowledge will be greatly reduced by a culture of collaboration and sharing, supported by robust IHTM-enabled standards, tools, and infrastructure. Impact on society will be helping to ensure that decision-makers are better informed through access to the best available information, resulting in better management of natural, financial, and other societally important resources.

Logic Model for Breakout 2.2: Software Engineering for Interoperability, Sustainability, and Improvement

2	3	6	5	4	1
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Current agency practices make software development time-consuming and expensive. Limited discovery, interoperability, and availability of existing software ecosystem. Significant time spent duplicating existing capabilities, components, kernels, and tools. Many codes available but often cannot be used together. Domain scientists, with limited understanding and use of modern software engineering practices, have developed siloed codes or cumbersome frameworks. Modern software development techniques not widely used. Current needs: 1. Better documentation 2. Test-driven development 3. Design.	RFP to prime the pump (incentives). Tools to support community.	Develop software working group to define IHTM collaborator capabilities and needs. Working group includes liaisons from relevant IHTM groups, Open science design group, academic/agency software engineer representatives. Adopt sustainable open-development practices in software engineering. Including 1) Unit testing, 2) Integration testing, and 3) Documentation generation. Review agency policy to allow open development of IHTM software. Interagency working groups for standard component interoperability. Interoperable standards for new software. Work with industry standard developers/maintainers (OGC, CNCF, W3C, etc.). Develop IHTM code style, implementation standards, and documentation. Incentivize open-development contributions.	Regular lyreviewed and community adopted standards. Language interoperability. Develop protocol and message exchanges standards. Expands support for a wide range of computing resources (laptops to supercomputers). Runtime-configurable component-based modeling ecosystem. Develop lowest-common-denominator kernels (regridding, simulation time). Community of software support.	System that enables robust and automated configuration of IHTM components within a unified, coherent framework. Components include: component management, data management, components/integration, workflow management, toolbox. Leveraging discoverable components in an automated way. Need to develop an interagency community of practice. Self-governance. Recovery of legacy software.	Reduce cost and time to produce and analyze IHTM model data. Reduce redundancies between agency investments. Leverage distinct strengths of contributors. Allows users to focus on science, not technical details. Provide a flexible software ecosystem for simulating and analyzing known stakeholder use-cases. Bringing modeling capabilities to stakeholders and the public in a transparent, well-documents, and actionable framework. Faster, deeper science. Efficient and simpler access. Accelerate discovery of sharable components. Extend model lifetimes. Enable the next generation of models to be part of a larger vision.

Logic Model for Breakout 2.3: Cross-Disciplinary Workflows: Analysis and Evaluation Requirements for Short-Term (< 1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Fragmented approaches to modeling tools and techniques. Existing workflows and frameworks are generally rigid and focused. Uncertainty quantification typically an afterthought. Some parochialism in terms of agencies needing identity and credit.	Internet of water. Existing workflow frameworks even though they are fragmented and can be rigid. Data and compute resources exist but are not collocated and openly available in all cases. Existing agency needs and some agreements.	Data assimilation/UQ standard practices. Data standards. Assess existing capabilities and identify gaps in versioning, data standards, etc. Build/strengthen relationships with users and stakeholders. Start to establish governance.	Agreements for formal data sharing among agencies. APIs and standards to enhance data sharing. Building libraries and tools as a community. Formalize relationships to promote co-production.	Sustained, seamless delivery of scale-relevant model results in a time-relevant manner. Generalizable, scalable, efficient, reusable workflows for environmental modeling. Collocated data and compute resources.	Repeatable, traceable, workflows lead to more efficient and robust hypothesis testing. Better understanding of agency science across agencies. Accelerating the pace of discovery. Holistic and interdisciplinary cooperation fosters improved communication.

Logic Model for Breakout 2.4: Cross-Disciplinary Workflows: Analysis and Evaluation Requirements for Long-Term (>1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Fragmented approaches to modeling tools and techniques. Uncertainty analysis is an afterthought. Challenges in repeatable or reproducible scientific approaches. Limited time and resources to work with a shared vision.	Multiple codes and data sources that can be better interoperated. Mandate for cooperation. Nationwide data sets that should be harmonized and made available in consistent, open ways. Bringing computing resources and data to the same places.	Strategic hire of an interagency lead to coordinate and motivate. Consolidation of data sets into nationwide, consistent, and open sets. Engaging stakeholders to seek ownership and financing. Common representation of space and time. Common tools for UQ from the start.	Further development of accessible and consistent data sets. Tools to enable repeatable operations for modeling and data analysis. Access to computing resources in the same place as the data. Scalable workflows that accommodate appropriate levels of complexity and transferability.	Tools for ensemble generation and evaluation. Stakeholder-informed UQ. Increased interagency collaboration.	Improved robustness and auditability of modeling for resource decisions. Increased pace of discovery. Improved collaboration improves communication. Better cross-disciplinary science. Better communication of risk.

Logic Model for Breakout 2.5: Building Computational/Modeling Testbeds: Requirements for Near-Term (<1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
No computation environment currently exists that can support collaborative, cross-agency development of an Integrated Hydrologic Terrestrial modeling capability. Significant challenges specific to an IHTM testbed include location, resourcing, governance, mission boundaries, security, interoperability, and connectivity. Related technical challenges include data access, version control, multi-scale modeling capabilities, coding, compute architecture and metric standards. A common computational testbed environment is needed to support: Cross-agency development Application testing Evaluation against standardized data sets Access to common software tools Current situation leads to duplicate and inefficient progress toward addressing Priority Water Challenges involving natural and human systems. -Distributed -Fragmented -Inefficient -Not interoperable	Multi-agency collaborative input is needed across observing and predictive modeling entities. Need a long-term commitment to entrain multi-disciplinary community. Data/inputs include forcing forecasts, land cover, and other data sets. Computational resource-related items include new model ideas to test, computer scientists, computational power, computational workflows, compute environments, and data security specialists.	Overall Near-Term Goal: Design for prototype testbed capability (ex. coastal flooding) Specifics: Identify the path to make the testbed open, accessible and flexible, Create an operational backbone workflow system for modeling development, Develop robust software protocols and access to resources for a testbed, Support standardization of existing facilities, measurement protocols, and data enabling real-time data discovery and modeling, Build common evaluation protocols, Near-Term Quick Win Activities: Catalog existing testbeds e.g., NOAA HMT, USACE CMTB, NASA SPoRT, DOE ILAMB, Scope and define common testbed evaluation protocols, Understand limitations and opportunities to leverage components, Scope a prototype of modular testbed framework.	Establish prototype testbed. Use cases for agency-relevant demonstration and evaluation /benchmarking. Community training resources.	An effective testbed for near-term prediction. Full-scale integration for coupled numerical and machine learning approaches. Capability to test subsets of models that are agency specific. Governance process that allows for testbed maintenance and evolution.	Improved coordination of decision support via better understanding of physical and human systems. Better representation of event impacts on stakeholders. Less duplication of effort and faster advancement for missions of participants. Increased collaboration in modeling approaches with stakeholders, modelers, and developers. Strengthened stakeholder confidence and trust in model output from increased transparency in development, reproducibility, and evaluation.

Logic Model for Breakout 2.6: Building Computational/Modeling Testbeds Requirements for Long-Term (>1 year) Prediction					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
No computation environment currently exists that can support collaborative, cross-agency development of an Integrated Hydrologic Terrestrial Model. Significant challenges specific to an IHTM testbed include location, resourcing, governance, mission boundaries, security, interoperability, and connectivity. Related technical challenges include data access, version control, multi-scale modeling capabilities, and coding and metric standards.	A number of governmental agencies research program have developed test beds. Model Intercomparisons (MIPs) are informative about differences but are limited in their ability to provide community consensus.	Provide resources and incentives for agencies and science community to participate in long-term test beds. Develop evaluation protocols and validate and benchmark existing test beds in order to understand overlapping capabilities, underlying assumptions in models and data set, and fundamental differences in workflow and analytics in order to scope flexible and community test beds. Develop test bed architect teams to prototype modular and compatible frameworks. Human activities modeling enhancements and integration in testbeds scoping.	A built and maintained virtual user facility (code, analytic tools, metrics, enable communities, collaboration, code development, multi-modeling workspace, visualization, training) to develop and use better models. Enhance testbeds with uncertainty and risk analysis capabilities.	A new computational testbed environment is needed to support the unique characteristics and requirements of an IHTM. Distributed across participating platforms as an “ecosystem of capacities”, this new testbed will support consistent multi-agency long-term projection activities. The ecosystem will be modular and able to mimic a supercomputing environment in terms of resources, security, and software availability. It will also need to support simple-to-complex modeling approaches, and have access to low-latency data feeds for forcing, assimilation, and validation. Code optimization tools to optimize run-times and minimize resource use, along with integrated validation capabilities, will also be essential.	A standardized environment that supports community development and funnels innovation into common platforms leveraged for both research and operations across a wide range of scales and integrated applications. The impact on science is measured by a better understanding of complex physical and human systems, robust across agencies and models, coordinated decision support. The gain to society includes community consensus and support on multi agency decisions. This IHTM testbed framework will provide a key linkage between IHTM groups and allow agencies to leverage community resources to achieve their respective missions in a more efficient and transparent way.

Logic Model for Breakout 3.1: Open Science by Design - Data Availability, Integration, and Interoperability					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Insufficient data are available or discoverable in public repositories. Data are spread across multiple repositories in different formats, and can be duplicated or deprecated without proper versioning schemes. This makes it difficult to discover and link data across systems. Data archives do not serve synthesis products while also preserving original observations. The data need to be linked with many models and tools; currently this takes a very long time. Data delivery can be brittle especially for large data sets. Lack of established rewards structure (funding, credit, etc.) for investing time in data management and related cyberinfrastructure. Need to serve data in a consistent manner by bridging different data collection protocols and data/metadata reporting formats for easy, robust access, and long-term preservation. The open data archives need to serve synthesis products while also preserving original observations.	Funding for repository managers to coordinate with researchers and agencies to work with each other. Funding needs to be tied to open release of code and data. Tools that make metadata collection easier. Incentive structures for stronger linkages between agencies.	Create an inventory of open data archives and practices/standards taking into consideration journal requirements. In particular, identify current best practices for making metadata generation easy, flexible, and effective, and develop metadata templates for priority measurements (e.g., sensor-based data acquisition). Convene a multi-institute workshop on data discovery and linking data to existing measurement networks. Engage publishing community to make open, standard data requirements for journals through interaction with data manager/data archive communities. Establish an incentive structure for making contributions that rewards openness with supplemental funding. Figure out what model output warrants long-term storage.	Coordinate with data working groups on citations and versioning of constantly evolving data products. Build momentum and enhance a community of practice for data integration that provides a path to serve data across agencies. Consolidate linkage between data repositories. Tools to improve discoverability and ingest data between repositories and modeling platforms. Formalize approaches to harmonize data such as the development of sensor data/metadata standards. Develop QA/QC standards and protocols. Fully document data collection, preservation protocols, and workflows for creating derived products, while preserving links to original observations. Make available some value-added derived products documented and seamlessly linked to original observations that are available for reanalysis as a demonstration of the value of preserving data with its provenance.	Serve useful forecasts for researchers, decision-makers, and citizens. Ensure data collection and preservation is well documented. Develop a national panel on hydrologic change (similar to IPCC) that defines IHTM outputs. Handle very large data sets and model outputs sustainably. Develop approaches to harmonize data and serve products with links to the raw data, descriptions of data collection/processing, and ability to communicate with the data provider. Moving beyond publication as the ultimate end products towards reproducible and meaningful products.	Dramatically improves the ability to find and use data easily from existing repositories. This will maximize the use of existing data, help identify data gaps, and enable prioritization of new data acquisition efforts. Accelerate discovery and enable better decision-making. Increase societal trust in science and scientific (data) products. Reduce duplication and increase the ability for large diverse teams to collaborate productively. A positive collaborative culture benefits everyone. Spur new markets for third-party products.

Logic Model for Breakout 3.2: Open Science by Design - Model Standardization versus Flexibility

2	3	6	5	4	1
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Unknown barriers to cross-agency collaboration. The best approach to community-driven standards is not defined.	Independently funded. Grassroots participation.	Short-term-meta model. Interchange formats. Cloud-hosted models.		IHTM management tool. Change agency culture to develop multi-agency culture.	Streamlined data analysis and exchange; collaboration between agencies.
Agency mission needs, security requirements, licensing, and information sensitivity limit the potential for collaboration to develop interoperable software.	Organizational support, policy consistency, maintain long-term vision, client apps.	Multi-tiered framework of standards that enables multi-agency participation in an IHTM. Develop academic and interagency working groups consisting of modelers, data scientists, and users. Inventory of current standards and how entrenched or flexible they are. Identify commonalities and needs for translators => Multi-tiered framework of standards.		Follow through on agreement to develop an IHTM with balance between flexibility and overarching coordination.	Common data pipeline and computing resources. Society will have access to products with actionable information that was previously unavailable.
No standards exist to ensure code/data interoperability.		Identify agency-specific limitations to IHTM collaboration. Define commonalities and outcomes of collaboration. Achieve agency buy-in. Identify interested parties to define requirements.		Establish standards that enable flexibility and extensibility to increase prediction power of models and physical understanding of the natural world.	Easier to compare model components. Build ensemble of models to characterize and reduce uncertainty. Entails R2O2R. More powerful model to understand more complex systems.
Cultural resistance to sharing of data, software, and process.		Identify cross-agency requirements. Training. Synthesize successful community codes. Look at data community for ideas.		Modeling framework that adapts and evolves with technologies and societal needs. Organizations converge on common modeling approach.	Better informed decision-making. Encourages "community of practice" around model concept. Allows addressing challenges at different scales.
		Flexible, scalable framework for inter-model communication.			Expedites coordination of R2O2R.
		Shift towards open development culture for data, software, and other research products. Review policies across agencies (licensing, security, use of commercial tools) and change where needed. Encourage partners to teach best practices. Encourage supervisors to honor open-source contributions.		Open science development is the norm in government-conducted and -sponsored research and practice (change performance metrics to reflect this).	Increased transparency in process of science; science education. Better reproducibility, faster discovery, more integration.

Logic Model for Breakout 3.3: Open Science by Design - Community Development and Outreach					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Need for definition of the community of model developers and users. Need for definition of stakeholders. Variable understanding/implementation of software design best practices. Disconnected funding opportunities, variable throughout sectors.	Existing groups involved with model code development using existing codes. Existing groups with experience in formally engaging stakeholders to assess their needs. Existing groups with experience in implementing/applying the existing models.	Catalog best practices. Develop a vision of community of communities, each bringing testbeds and codes to the table. Create a multi-agency committee charted to facilitate communities of practice with support from the various agencies.	“Evolution”: give multiple models the opportunity to compete and retain the best/strongest. Develop a cadre of champions. Work toward a coordinated strategy for documentation and workflows to make learning and using the IHTM tools clear.	Settle on and commit to tools and interaction protocols.	Science improved with greater interaction across domains and with stakeholders. Society benefits with improved decision-making.

Logic Model for Breakout 3.4: Business and Funding Models

2	3	6	5	4	1
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Agencies share water responsibilities, but their distinct business and funding practices may not fully support the collaborative development of IHTM capabilities, methods, tools, and communities of practice that will advance the science and thus individual agency missions.	Many examples of interagency coordination and governance work well and could serve as examples for how to establish, fund, and govern an IHTM capability. Potential examples include: Joint Center for Satellite Data Assimilation, Decadal and Regional Climate Prediction using Earth System Models (EaSM), Multi-Resolution Land Characteristics Consortium, Earth System Grid Federation (ESGF), Scenarios and Interpretive Science Coordinating Group (SISCG), JALBTCX, USCG/USACE National Automated Identification System (NAIS). Existing principles/concepts of open science by design, if widely adopted by the agencies and communities of practice, could provide a framework for community governance and the collaborative development of an IHTM national capacity.	Learn from best-in-class examples. Skin in the game for early wins and pilot projects using flexible approaches. Create new and/or leverage existing community of practice working groups. Agencies fund dedicated liaisons to working groups. Establish interagency coordination (e.g., working group) on interagency coordination and governance.	Identification of non-traditional funding sources – new processes needed for nimble public-private partnerships. Responsiveness to both top-down and bottom-up opportunities. Develop five-year strategic plan/interagency roadmap.	Business and funding models exist to incentivize and facilitate multi-agency support/engagement in IHTM to meet agency missions. Agencies evolve business and funding practices for optimum impact.	Effective stewardship and efficient use of federal resources. More seamless interagency capabilities. Transparency and less confusion in traversing the federal landscape for capabilities (the public) and resourcing (the science community). Vastly improved leveraging of the nation's science assets through an R2O and O2R framing, enabled by mission alignment and improved business and funding practices.

Logic Model for Breakout 3.5: Mission Alignment with IHTM					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Many agencies share water responsibilities, but each agency has a specific mission and niche to fill in meeting the nation's water challenges. Although all groups need accurate simulations of the hydrologic cycle to fulfill their initial missions, the status quo is for each agency, or even individual groups within agencies, to develop their own models. Budgeting and mission goals are often independently planned, contributing to the fragmentation of data, modeling, and computing resources/ Legal and structural barriers often define mandated missions and may complicate collaboration.	IHTM workshop included a broad range of agency representatives extending from undersecretaries, to senior executives, program managers, active scientists and engineers, and resource managers and operations managers. The recognition and support for the need for an IHTM capability by this wide spectrum of the community is a necessary and powerful resource for moving the ideas from concepts to actions. Support from high-level managers within agencies is an especially important input/resource that will enable a range of technical staff to engage in cross-agency planning and development. Another vital resource is the talent and committed support of program managers and technical staff to develop prototype designs and early examples of IHTM development. Perseverance and intrinsic motivation: The IHTM capability can be initiated through pilot projects sponsored by early adopters. But full development of the capability will require a sustained effort from a larger spectrum of motivated scientists, practitioners, managers, and appropriators. This long-term effort needs to be motivated by the perceived benefits to each agency in order for it to be sustainable.	Identify pilot projects for early wins ("confidence-builders") that can be carried forward by motivated early adopters who have management/agency support (buy-in). Develop joint solicitation for pilot collaborative projects or a common case study with shared vocabulary established. Learn from experience: Review business models for large collaborative initiatives with multiagency engagement, and then replicate key aspects of successful business models (e.g., GLRI), and avoid the pitfalls of less successful business models. Agencies identify their own needs from an IHTM capability, contribute to design requirements, and identify potential contributions towards development. Agencies recognize the need for change and facilitate collaboration and cultural exchange between technical communities towards establishing IHTM use cases and communities of practice. Develop a clear communication plan for the IHTM road map to facilitate efficient and broad participation. All agencies agree to openly share data.		Agencies coordinate budget requests and mission goals to achieve mission alignment. Establish clear common goal(s) to inspire a community to contribute and leverage resources and relationships among agencies. Establish a sustainable governance strategy that engages across sectors and agencies. An inspired community working productively together and supported by senior agency leadership. Establishment of effective incentive and reward structure at agency and community levels. Coordinate budgets and mission goals to implement the technology and infrastructure for data sharing and live real-time simulations, leading to actionable water intelligence. Institutionalized collaboration across agencies that builds awareness and shared culture, is supported at a high level, and is productive and lasting.	Satisfy the core mission of each agency while maximizing efficiency, resource allocation. A joint IHTM platform will allow each agency to meet its mission requirements with agility and efficiency while benefitting from and contributing to cross-agency capabilities. Shared vocabulary, information, and operations to improve decision-making. Faster, more efficient science pipeline, producing more impactful and broadly useful scientific products. Accelerate scientific discovery, enabling improved, more reliable predictions. Accelerate the delivery of actionable information and services to stakeholders to better inform policy decisions and increase public trust. Improved situational awareness of hydrologic state of the landscape, improving societally relevant mission support.

Logic Model for Breakout 3.6: Interagency Coordination and Governance					
2	**3**	**6**	**5**	**4**	**1**
Current Situation	Inputs/Resources	Near-Term Goals (1-3 years)	Mid-Term Goals (4-6 years)	Long-Term Goals (7-10 years)	Outcomes (impacts on science and society)
Integration across multiple agencies, each with a shared vision of the IHTM, faces significant challenges. At present, agencies are focused on their individual missions, and how their individual technical and geographic areas of expertise serve those missions. Even though there are beneficial capabilities and expertise that could be transferred between agencies, it's easier to identify barriers to this transfer than to actively pursue it. For example, (1) current momentum and legacy tools may prevent adoption of software engineering best practices; (2) differing cultures and languages hinder collaboration; (3) the gap between research and operations; (4) and a perceived competition for limited resources. The challenge is to shift away from these excuses and establish a vibrant and diverse inter-agency community that supports the development of the IHTM.	Funding Executive committee Top level technical committee Cross-agency communities of practice (COP)	Develop a charter Initiate small number of cross-agency COP with specific short term achievable goals Develop an actionable roadmap for how the COPs would come together underneath an IHTM governance structure Develop a clear understanding of shared objectives, mapping agency overlap, understanding the incentives for collaboration, and developing a communication structure to enable cross-agency collaboration		Barrier-less, institutional collaboration across agencies that creates a new culture, is supported by the agency leadership, is productive and lasting, and more effectively and holistically enables agencies to meet mission objectives	An approach to coordination and governance will be established that enables the co-development of the IHTM software ecosystem, across agencies and across the research/operations boundary, such that the best science and algorithms are integrated without being encumbered by agency boundaries or mission. The scientific teams building these models will be supported in ways that help them ensure that these advances in IHTM scientific capacity serve both the broader community as well as the missions of collaborating agencies. Mechanisms will be developed to ensure each agency will contribute time, staff and resources in a way that fairly balances the community (their expertise, and resources), with their mission benefit.

Appendix D: Use Cases

During the workshop planning period, the Interagency Executive Planning Team solicited short use-case descriptions from the participating agencies and the academic community. These examples are intended to highlight specific applications that motivate development of a community IHTM capability. Over 50 use cases were submitted, each following a prescribed one-page format. For reference, the use case slides are reproduced in this appendix. A summary listing (index) of the use case titles and submitting persons/organization is provided here.

1. Sediment/Nutrient Transport in the Mississippi *(Department of Energy)*
2. Integration of Watershed Hydrology, Reservoir Water Quality, and Operations *(Bureau of Reclamation)*
3. Nutrient Loading in the Mississippi Basin *(U. S. Department of Agriculture)*
4. Management Representation in Water Resource Planning and Assessment Models *(Bureau of Reclamation)*
5. Aging Dam and Levee Infrastructure and Dam Breach Analysis *(U. S. Department of Agriculture)*
6. Delaware River Basin *(U.S. Geological Survey)*
7. Delaware Bay: Groundwater Salinization and Ground Subsidence *(U.S. Geological Survey)*
8. Lake Erie Hypoxia *(National Oceanic and Atmospheric Administration)*
9. Lake Erie Nutrient Loadings *(National Oceanic and Atmospheric Administration)*
10. Lake Erie Harmful Algal Blooms *(National Oceanic and Atmospheric Administration)*
11. Upper Mississippi River Basin and Eastern Corn Belt *(U. S. Department of Agriculture)*
12. Central Mississippi River Basin *(U. S. Department of Agriculture)*
13. Nutrients and Gulf of Mexico Hypoxia *(U.S. Geological Survey)*
14. Nutrients, Harmful Algal Blooms, and Toxic Algae *(U.S. Geological Survey)*
15. Integration of Surface and Subsurface Hydrologic and Hydraulic Models *(U. S. Department of Agriculture)*
16. Gunnison River Basin *(Department of Energy)*
17. Linked Longitudinal (Instream) and Lateral (Groundwater) Flows in Regulated River Corridors *(University of Texas Austin and Utah State University)*
18. Integration of National Water Model (NWM) and Hydrologic and Water Quality System (HAWQS) *(U.S. Environmental Protection Agency)*
19. Mississippi River Basin Water Quality (N) Modeling with River Corridor Exchanges *(Vanderbilt University and University of Texas Austin)*
20. Carbon Cycling by River Corridors of the CONUS *(Vanderbilt University, University of Texas Austin, Department of Energy)*

21. Fully Coupled Modeling of River Corridors (i.e., Including Riparian, Parafluvial, and Hyporheic Zones) *(Penn State University, University of Texas Austin, Department of Energy)*
22. Assessing Surface-Groundwater Flows in Regulated Rivers using Component-Based Models *(Utah State University, University of Texas Austin)*
23. In- and Near-Field Modeling and Data Needs for Effective Nutrient Management *(Environmental Protection Agency)*
24. International Basins *(Bureau of Reclamation)*
25. Multi-Objective IHTM Modeling: Non-Climate Factors *(U.S. Army Corps of Engineers)*
26. Water Resource Allocations and Planning *(U.S. Army Corps of Engineers)*
27. Western U.S. Water Management for Multi Sector Analyses *(Department of Energy)*
28. San Juan Watershed - Management for Multi Sector Analyses *(Department of Energy)*
29. Groundwater Banking in the Western U.S. *(Department of Energy)*
30. Natural / Virgin Flows *(Bureau of Reclamation)*
31. Modeling Complex Groundwater-Surface Water Interactions *(Bureau of Reclamation)*
32. Integration of Watershed Hydrology, Reservoir Water Quality, and Operations *(Bureau of Reclamation)*
33. Snow Modeling and Forecasting for the State of California *(U.S. Department of Agriculture)*
34. Incorporate Channel Transmission Losses into the WRF Hydrologic Model to Improve Estimate of Recharge, Water Availability, and Flood Peaks in Arid & Semiarid Environments *(U.S. Department of Agriculture)*
35. Aging Dam and Levee Infrastructure and Dam Breach Analysis *(U.S. Department of Agriculture)*
36. Land Stewardship Use Case: A Solution to "Go-Back" Land—Restoring Abandoned Farmland and Sustaining Rural Communities *(U. S. Department of Agriculture)*
37. Hydro-Economic Resilience & Western Water Stress (FEWSION) *(Northern Arizona University)*
38. Water Sustainability for Managed Watershed Systems: Columbia River Basin Use Case *(Department of Energy and Vanderbilt University)*
39. Meeting Future Water Needs to Accommodate Western Population Growth *(U.S. Environmental Protection Agency)*
40. Groundwater depletion as a coupled human and natural system *(Department of Energy)*
41. Integration of Coastal and Hydrologic Models *(U. S. Army Corps of Engineers)*
42. Urban Flooding *(U. S. Department of Agriculture)*
43. Flooding During Extreme Events *(National Oceanic and Atmospheric Administration)*
44. Springtime Ice Jam Flooding in the Northeast *(Department of Energy)*
45. Forecasting Impacts of Disturbance Events in the Rocky Mountain West *(University of Colorado Boulder)*

46. Flooding for Mid-Atlantic Coastal Localities *(Virginia Institute of Marine Science)*
47. Precise Near-Realtime Urban Flood Detection and Prediction (FloodAware) *(Northern Arizona University)*
48. Lake Champlain-Richelieu River Flood Forecasting *(National Oceanic and Atmospheric Administration)*
49. Compound Flooding in Miami-Dade County *(University of Central Florida)*
50. Lower Ohio-Mississippi River Flood Control *(National Oceanic and Atmospheric Administration)*
51. Frozen ground affected flooding in glacial landscapes *(U.S. Geological Survey)*
52. Post-Wildfire Impacts to Flood Risk Management: Las Conchas Wildfire – New Mexico *(U.S. Army Corps of Engineers)*
53. Hurricane Irma, Florida, 2018 *(U.S. Army Corps of Engineers)*
54. Great Lakes Water Level Forecasting and Management *(National Oceanic and Atmospheric Administration)*

Appendix E: Use Case Slides

Sediment/Nutrient Transport in the Mississippi

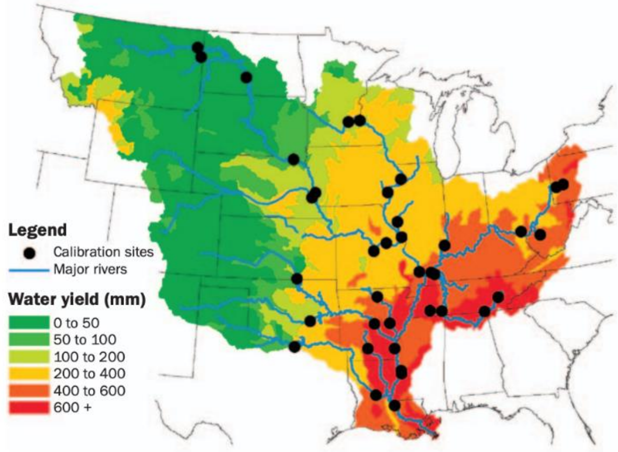
Water-related challenge(s): Water quality is modulated by meteorological and hydrologic drivers through surface energy and water balance. Sediment and nutrient inputs along rivers are particularly important for driving hypoxia in the coastal zone, and play a key role in carbon and nutrient cycling. With this in mind, a IHTM model of the Mississippi would greatly assist in both stakeholder-relevant and scientific investigations of this watershed.

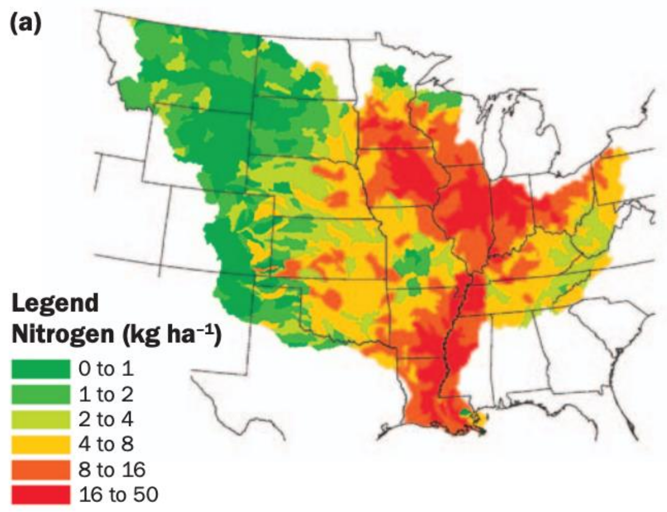
Context: The Mississippi is heavily managed, and so any study of water quality must incorporate land-use, meteorological, hydrologic, water management practices. These four categories of processes are deeply intertwined, necessitating a comprehensive approach to modeling of this interconnected system.

If IHTM capability existed, how would it enhance our ability to address the problem(s)?
Given the highly interconnected nature of this system, changes to the watershed (such as from climatic shifts or land use / land cover change) need to be considered holistically in order to perform meaningful planning. Consequently, IHTM is essential to meaningful study of sediment/nutrient transport in this system.

If IHTM capability existed, how would it impact and benefit:
Society: provide better tools to stakeholders to understand the impacts of their decisions on the Mississippi watershed.
Science: understand the interplay between relevant and interconnected factors that affect the behavior of this watershed.

DOE, Multi-Sector Dynamics program area





Source: White et al. (2014) “Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation”

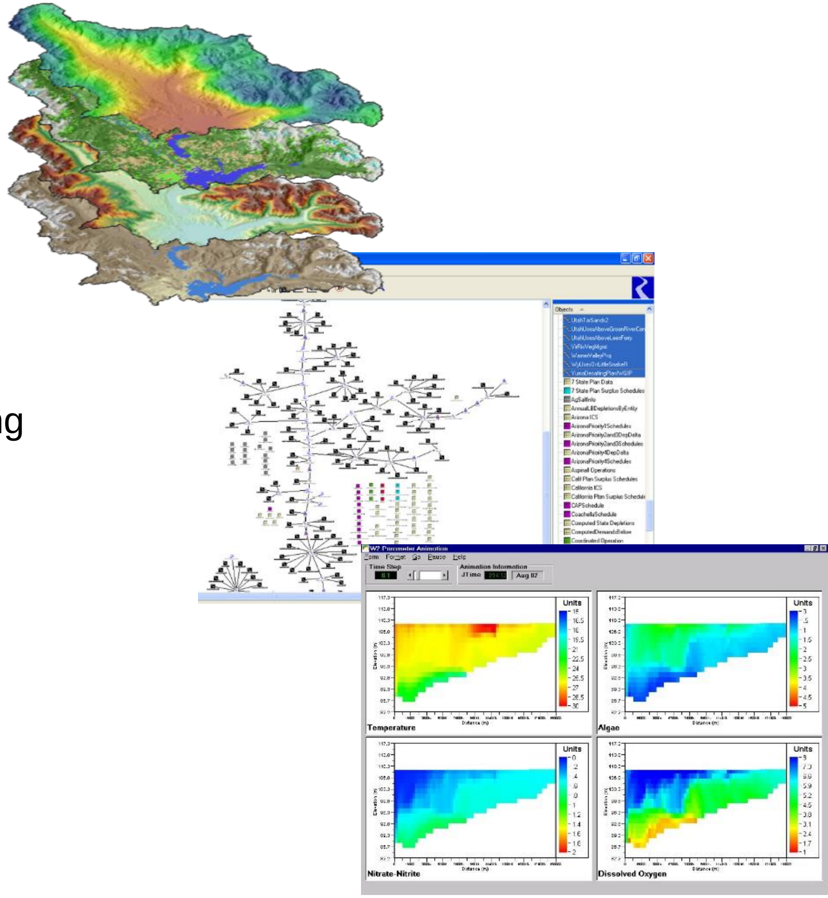
Potential Stakeholders : DOE, USDA, USGS, Water managers, States, Reclamation
Potential “Users”/”Operators” of IHTM Capabilities: DOE, USGS, Water managers, States, Reclamation
Potential “Developers” of IHTM Capabilities: DOE, USGS, NSF, Reclamation

Scientific and Technical Challenges for IHTM Development:
Several federally funded models (i.e. SWAT, ELM) exist that support sediment/nutrient/pesticide/pathogen transport in rivers. However, developing a comprehensive model of the Mississippi requires bringing together data and resources from many different agencies at all levels.

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: <need to harmonize capabilities with other agencies>
Development of new capabilities: <harmonize assumptions, develop datasets, new couplings>

Phased Approach to Development:

Integration of watershed hydrology, reservoir water quality, and operations



Place: Grand Lake, CO; part of the Colorado Big Thompson Project

Problem(s): physically-based models of hydrology and water quality are used with an operations model to adaptively manage the Three Lakes System and the greater Colorado Big Thompson project. Both hydrology and operations impact the water quality in Grand Lake so operating this system optimally (for water deliveries and to meet water quality goals) requires a system that accounts for the feedbacks between operations, watershed hydrology, and water quality.

If IHTM capability existed, how could it be used to better address the problem(s)? Integrating these models (or providing a smooth path for running them together) in a real-time or forecasting application would provide needed information to better manage this system.

Potential Stakeholders: Reclamation, NPS, USFS, local governments and water providers
Potential "Users" of IHTM Capabilities: Reclamation
Potential "Developers" of IHTM Capabilities: Reclamation, others?

Scientific and Technical Challenges for IHTM Development:
- Computing demands for real time applications with multiple scenarios
- Model validation for stakeholder confidence
- Incorporating forecasting data

Impact of IHTM capability to
Society: Minimize water quality influence of operations while maintaining water deliveries
Science: Diverse processes requiring flexible framework

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities:
Development of new capabilities:

Phased Approach to Development:
Near-Term (0-2 yrs): Loose coupling
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs): Incorporation of forecasting

Bureau of Reclamation

Nutrient Loading in the Mississippi Basin

Scenario/Place: Mississippi River Basin
Problem: The hypoxic zone in the Gulf of Mexico forms every summer and is a result of excess nutrients from the Mississippi/Atchafalaya River and seasonal stratification (layering) of waters in the Gulf.
Potential Stakeholders: Communities, States, Industry, Agriculture.
IHTM Role: Integration of hydrologic and hydraulic models, groundwater , ecosystem models, and plant growth and agricultural management models across agencies could allow integrated solutions to develop policy to reduce the size of the hypoxic zone.
Potential IHTM Customers: USDA, EPA, USACE, State Environmental Agencies, and the Mississippi River/Gulf of Mexico Hypoxia Task Force.
IHTM Impacts:

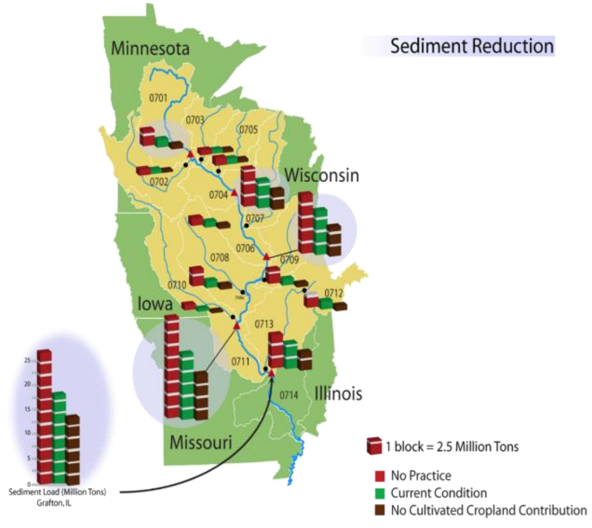
- *Scientific:* New basin scale ecohydrological models that simultaneously consider geographic, environmental, and land management factors.
- *Societal:* Coordinated tools to develop comprehensive agricultural management policy to mitigate hypoxia.
- *USDA mission*: Tools for use in Farm Bill debate and in setting national conservation policy.

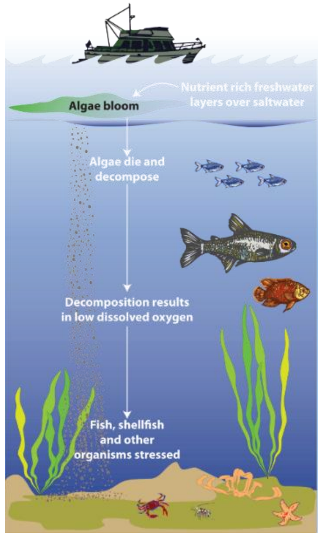
IHTM Needs:

- National dataset of agricultural management practices.
- Seamlessly couple/develop surface, groundwater, and land management components and data types
- Flexibility to transfer output and visualize key information of interest by different stakeholders.

Scientific and Technical Challenges for IHTM Development: Parallelization and optimization of coupled codes, Standardized I/O, Model coupling and validation, Access and linking to forcing and assimilation data

Potential IHTM "Developers": USDA, Universities (Texas A&M, Colorado State, Purdue, and others), USGS
Key Milestones:
Near-Term (0-2 yrs): Real time forecasting of all fields in MRB.
Mid-Term (2-5 yrs): Calibrated and validated model for water, sediment and nutrients.
Long-Term (5-10 yrs): Refine calibration and perform scenario analysis.





USDA POC(s):
Jeff Arnold, ARS, (254)931-4010,
Jeff.Arnold@usda.gov

Management Representation in Water Resource Planning and Assessment Models

Place: broadly anywhere; case study the Upper Rio Grande River watershed

Problem(s): physically-based models including hydrology, land surface, and groundwater models, need to be coupled together with water management models to accurately quantify water resource processes. For example groundwater pumping rates are impacted by surface water management decisions, and groundwater pumping then has a feedback on future surface water management decisions.

If IHTM capability existed, how could it be used to better address the problem(s)? It could allow for models to be more easily coupled, and for data to be exchanged time-step by time-step between models

Albuquerque Journal/ AP Photo/Susan Monto

Potential Stakeholders: Reclamation, USGS, USACE, CU Boulder
Potential "Users" of IHTM Capabilities: Agencies/Institutions………….
Potential "Developers" of IHTM Capabilities: Agencies/Institutions…………

Scientific and Technical Challenges for IHTM Development:

- Model integration; dynamic feedback
- Representing disparate complex processes (physical and operations) in the same modeling framework
- Data management; development of inputs to support all modeling

Impact of IHTM capability to

Society: Improved operational policy; improved water management
Science: Improved understanding of coupled and managed systems

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities:
Development of new capabilities:

Contact:

Ken Nowak
knowak@usbr.gov

Phased Approach to Development:

Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

Aging Dam and Levee Infrastructure and Dam Breach Analysis

Water-related challenge(s):

- Hazard Creep – Change in land use from agriculture to urban creating an increase risk for loss of life if dam failure were to occur.
- Aging infrastructure with structural deterioration and sedimentation of reservoirs reducing flood storage.
- Lack of real-time reservoir and dam/levee data for monitor drought and flood conditions.

Place: Nationwide across urban, suburban, and rural settings.

Primary Stakeholders: USDA-Natural Resources Conservation Service, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Federal Emergency Management Agency, National Weather Service, U.S. Geological Survey, State Dam Safety Offices, National Association of Conservation Districts, Emergency Managers, Floodplain Managers, Insurance Associations, Lending Institutions, Rural Water Districts, and Municipalities.

If IHTM capability existed, how could it be used to better address existing challenges? IHTM capacity would allow integration of current and new monitoring data with historic data. Improve hydrologic and soil parameter inputs for dam and/or levee breach prediction. Lead to development of new technology and beneficial uses dams and reservoirs have to offer. Discovery of new approaches for maintaining a proper balance from our uplands to our rivers' outlet.

Scientific and Technical Challenges for IHTM Development:

- Standardization of instrumentation and higher density sensor network needed in vicinity of reservoirs, dams, and levees.
- Reliable and/or new ground penetrating technology for mapping dams and levees.

IHTM Impact Scientific:

- Improves coordination and sharing of data.
- Expands the access to large data sets for a wider range of computational model utilization.
- Identifies new avenues for research for improving the design and analysis of safe, economical structures and channels for the conveyance, storage, disposal, and measurement of runoff waters.

IHTM Impact Societal:

- Allow emergency managers and state dam safety offices to access data for improving emergency action plans.
- Informs policy makers in the development of zoning regulations and insurance policies.
- Allows lending institutions to make better risk informed decisions in residential and businesses impacted by flooding.
- Safeguard food, water, infrastructure, and natural resources through flood protection.

Key Milestones:

- Near-Term (0-2 years): Identify data sources, integrate current and historic data, and identify and agree to standardization of instrumentation for monitoring system.
- Mid-Term (2-5 years): Set-up pilot program for monitoring reservoir and dam/levee network and begin development of data sharing platform.
- Long-Term (5-10 years): Expand reservoir and dam levee monitoring network and begin development of public interface for emergency managers, state dam safety officials, etc.

Contact Information:

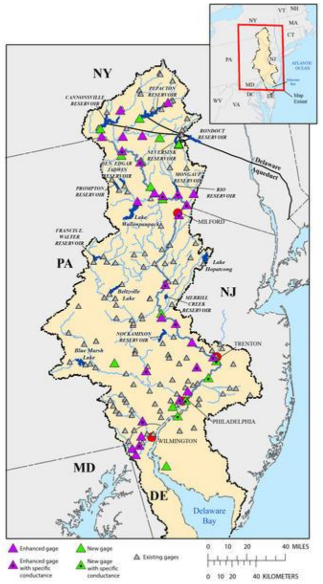
Sherry Hunt, (405) 624-4135 ext. 222; Sherry.Hunt@usda.gov
USDA-ARS, Hydraulic Engineering Research Unit, Stillwater, OK

EXAMPLE: Use-Case for the Delaware River Basin

Water-related Challenge(s):

- Water resources in the Delaware River watershed are vulnerable to salt intrusion (The City of Philadelphia during drought)
- Releases of freshwater from upstream reservoirs required to reduce salt concentrations at intake (quantity issue during drought).
- Future sea level rise and physical changes to the estuary will likely increase this risk.

Context: The Delaware River basin supplies water to over 15 million people, with 60% of drinking water coming from surface water sources. The Delaware River is the longest undammed river in the Eastern United States and flows into one of the largest freshwater estuaries. 11 municipalities withdraw water directly from the Delaware River.



If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for an integrated assessment of water availability for ecosystem and human needs under drought conditions that can include saltwater intrusion and reservoir operation.

Potential Stakeholders: The City of Philadelphia, The Delaware River Basin Commission, Decree Parties (NYC, PA, NY, DE, NJ)
Potential "Users" of IHTM Capabilities: USGS WSCs, William Penn Foundation, Stroud Center, Delaware River Basin, Drexel University
Potential "Developers" of IHTM Capabilities: USGS WMA, USGS WSCs, DOE, NOAA

Scientific and Technical Challenges for IHTM Development: Parallelization and optimization of coupled codes, Standardized I/O, Model coupling and validation, Access and linking to forcing and assimilation data

Impact of IHTM capability to

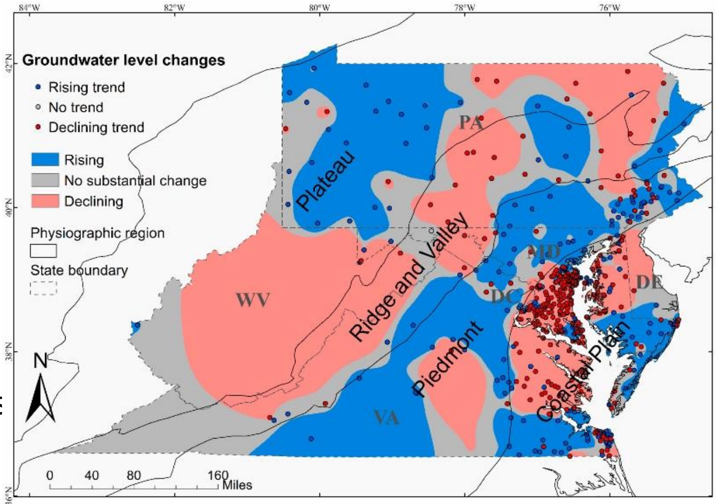
- *Scientific:* Coupled models that integrate reservoir operation, saltwater intrusion, drought and ecosystem and human needs for water.
- *Societal:* Reduced risk to sustainable water supply in a highly populated region of United States.

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that accounts for salt intrusion

Delaware Bay: groundwater salinization and ground subsidence

Water-related Challenge(s):

- Groundwater is an important source of drinking water in Delaware Bay region
- Sea level rise and groundwater extraction will lead to salt intrusion into shallow freshwater aquifers
- Ground subsidence due to groundwater withdrawals may accelerate local relative sea level rise rates
- Salt intrusion into shallow coastal aquifers will impact agricultural land use and coastal ecosystem health.



Dong et al., 2019

Context: Groundwater supplies 40% of drinking water supplies in Delaware Bay region. Along the Atlantic seaboard ground subsidence due to groundwater withdrawals has led to higher rates of relative sea level rise increasing flood risks. Extraction of shallow coastal groundwater accelerates salt intrusion into coastal aquifers and impacts nutrient loading to coastal waters.

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for an integrated assessment impact of human groundwater demands on the patterns and rates of groundwater salination and subsidence.

Potential Stakeholders: States of Delaware and New Jersey, local water municipalities, farmers, and DRBC
Potential "Users" of IHTM Capabilities: USGS WSCs, Delaware GS, EPA, DNREC
Potential "Developers" of IHTM Capabilities: USGS WMA, USGS WSCs, DOE, NOAA, University of Delaware

Scientific and Technical Challenges for IHTM Development: Parallelization and optimization of coupled codes, Standardized I/O, Model coupling and validation, access and linking to forcing and assimilation data

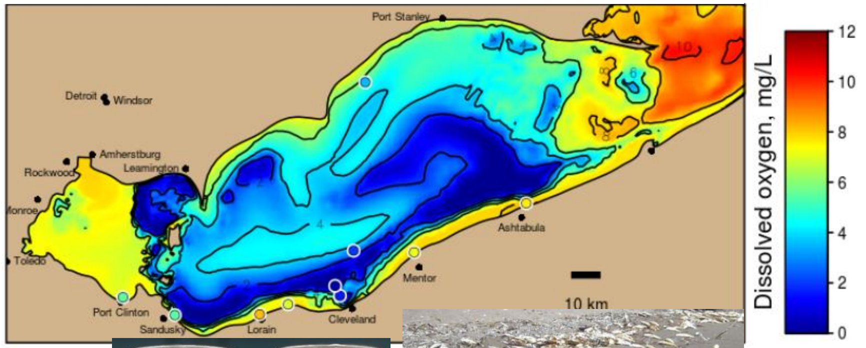
Impact of IHTM capability to

- *Scientific:* Coupled models that integrate groundwater recharge, well pumping rates, SLR, and salt intrusion, drought, flooding, and ecosystem and human needs for groundwater.
- *Societal:* Reduced risk to sustainable water supply in a highly populated region of United States.

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that accounts for salt Intrusion and subsidence

Use-Case for Lake Erie Hypoxia

Lake Erie Bottom Dissolved Oxygen



Water-related Challenge(s):

- Lake Erie hypoxia is a symptom of excessive watershed nutrient loading and is also affected by lake temperature and hydrodynamics
- Nutrient load targets for hypoxia control are more uncertain than for HABs control
- When hypoxic water enters drinking water intakes, it can cause service pipe corrosion and create health risks associated with elevated levels of manganese

Context: Up to 3,000 square miles of Lake Erie experience hypoxia between July and October. <u>Economic and societal impacts include</u>: ●risks to public water systems – hypoxic water is corrosive and/or contaminated with metals released by sediments ●reduced summer habitat for recreational and commercial fisheries ● diminished effectiveness of efforts to control eutrophication due to internal loading of phosphorus from hypoxic sediments

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM would improve accounting of nutrient inputs to the lake, transport of nutrients and biological production within the lake, and, ultimately, targets for reducing nutrient loading to control hypoxia

Potential Stakeholders: Public water utilities*, recreational anglers*, and coastal communities *existing stakeholders in our hypoxia work
Potential "Users" of IHTM Capabilities: NOAA, CIGLR, USGS, DFO Canada, OH EPA, PA DEP, Cleveland Water
Potential "Developers" of IHTM Capabilities: NOAA, CIGLR, USGS

Scientific and Technical Challenges for IHTM Development: Predicting nutrient loading from small and mid-sized tributaries to the lake where discharge and nutrient data are sparse

Impact of IHTM capability to

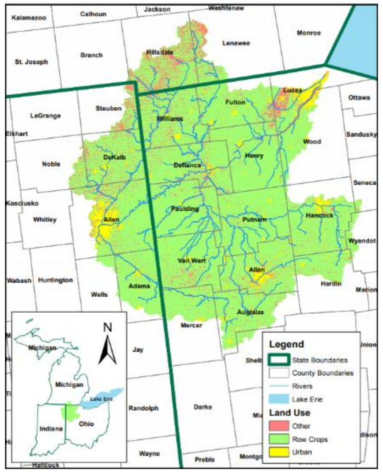
- *Scientific:* Improved targets for nutrient load reductions required to minimize the impact of hypoxia

- *Societal:* Protected drinking water safety and aesthetics, productive and sustainable fisheries

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that predicts hypoxic extent and duration

GLERL and CIGLR: POC

Use-Case for Lake Erie Nutrient Loadings



Water-related Challenge(s):

- Lake Erie's Western Basin is experiencing Harmful Algal Blooms due to excess phosphorus loading, primarily from agricultural sources.
- Management of agricultural fields in the Maumee River watershed is a critical factor determining nutrient loading to Lake Erie, which drives the annual severity of Harmful Algal Blooms.
- Future climate conditions are likely to lead to more intense rainfall patterns during the months in which nutrient loadings to Lake Erie are most critical for algae development.

Context: Lake Erie supports over $17 billion to the regional economy and supplies 11 million people with drinking water. The Maumee River watershed is the largest watershed of Lake Erie, and of the Great Lakes, and contributes the largest loads of phosphorus to Lake Erie. Over 80% of the land use within the Maumee River watershed is agriculture. Many models, and supporting data, have been developed for contributing watersheds, as well as for Lake Erie; however, they are not well integrated.

If IHTM capability existed, how could it be used to better address the problem(s)?

An IHTM would allow for an ability to improve assessments of the linkages between human behavior, economics, watershed dynamics, and lake processes. This would lead to more robust understandings of how farmer decisions upstream of Lake Erie affects nutrient loading to the lake and how this nutrient loading affects algal development in the lake. This integrated model would allow also for more robust analyses on the effectiveness of different agricultural practices and land use policies in reducing Harmful Algal Blooms in Lake Erie.

Potential Stakeholders: State Agencies (i.e., Ohio EPA, Ohio Department of Agriculture), Federal Agencies (i.e., USDA), Nonprofits (i.e., The Nature Conservancy), Agricultural Commodity Groups (i.e., Ohio Corn and Wheat).

Potential "Users" of IHTM Capabilities: International Joint Commission, federal agencies (i.e., USDA, USEPA), state agencies (i.e., Ohio EPA, Ohio Department of Agriculture), academic institutions (i.e., Ohio State University).

Potential "Developers" of IHTM Capabilities: Federal agencies (i.e., USDA, USGS, NOAA), academic institutions (i.e., Ohio State University, Heidelberg University), and consulting firms (Limnotech).

Scientific and Technical Challenges for IHTM Development: Integrating existing watershed, human-behavioral, and economic models of the Maumee River watershed with existing lake models of Lake Erie.

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate human behavior models of farmer land use decisions, watershed models, and lake models.
- *Societal:* Reduced occurrence of Harmful Algal Blooms in a critical freshwater body.

GLERL POC

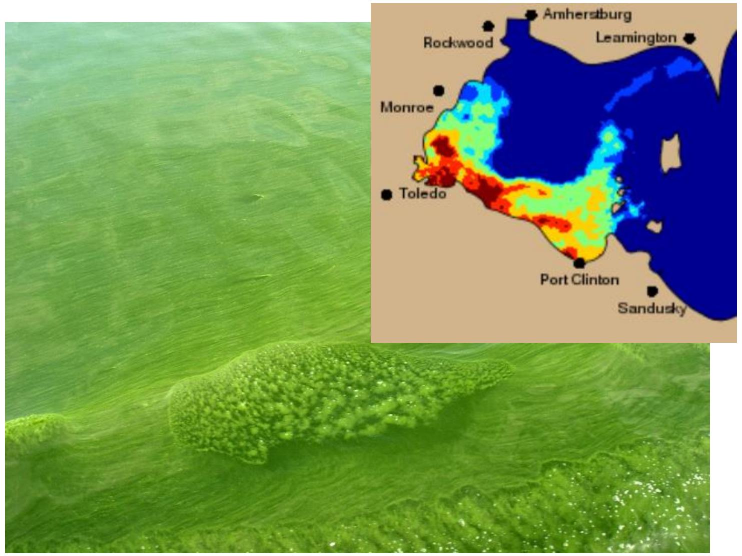
Key Milestones:

Near-Term (0-2 yrs): Individual human-behavioral, economic, and watershed models of the Maumee River watershed and lake model of Lake Erie

Mid-Term (2-5 yrs): Coupled dynamic human-behavioral, economic watershed, lake models

Long-Term (5-10 yrs): Fully integrated system that assesses impacts of changing environment, economic, policy conditions on Harmful Algal Blooms and water quality of Lake Erie

Use-Case for Lake Erie Harmful Algal Blooms



Water-related Challenge(s):

- Cyanobacteria Harmful Algal Blooms (cHABs) in western Lake Erie impact drinking water plants, recreation, and charter anglers through production of toxins and diminished aesthetic quality.
- Nutrient loading (phosphorus and nitrogen) from agricultural watersheds fuels the blooms.
- Changing patterns of precipitation quantity, timing, and intensity influence nutrient loads.
- Increased water temperatures promote the growth of cHABs.

Context: Lake Erie HABs have the potential to affect water supplies of 2.5 million people in Ohio and Michigan

If IHTM capability existed, how could it be used to better address the problem(s)?

The ability to forecast non-point source runoff, river discharge and nutrient loading, linked to a biophysical model of Lake Erie HABs, has the potential to improve forecasts of HAB intensity, transport, and toxicity.

Potential Stakeholders: Coastal communities in Ohio and Michigan, recreational users of Lake Erie, charter anglers, with the potential to extend to other lake systems within the US.

Potential "Users" of IHTM Capabilities: NOAA, USGS, academic researchers, state agencies
Potential "Developers" of IHTM Capabilities: NOAA, USGS, academic researchers

Scientific and Technical Challenges for IHTM Development: Accurate calibration of modeled river discharge for specific watersheds within a national framework. Prediction of nutrient loads, which would require information on agricultural land use and practices.

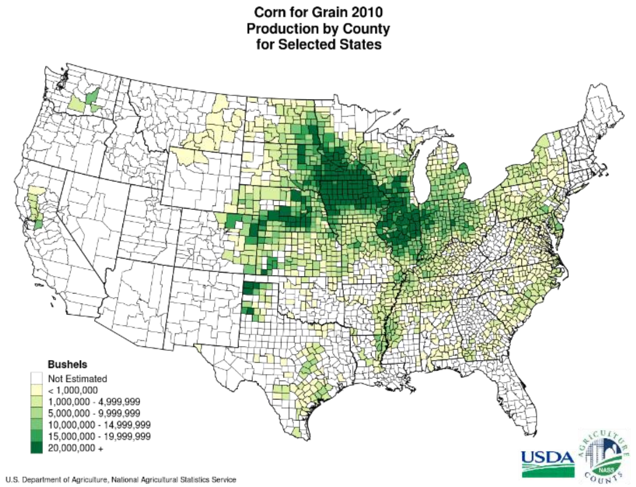
Impact of IHTM capability to

- *Scientific:* Coupled watershed and biophysical models to predict ecological endpoints.
- *Societal:* Improved provision of drinking water, fisheries, and recreational use to millions of people.

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that accurately predicts river discharge and nutrient loads

GLERL POC

Use-Case for the Upper Mississippi River Basin and Eastern Corn Belt



Water-related Challenge(s):

- Soils in the region are permeable, but topography means they must be artificially drained for production
- Nutrients are prone to leakage out of the drained systems
- Loadings to river systems causes hypoxia in receiving waters, the Great Lakes and Gulf of Mexico

Context: The US Corn Belt is a highly productive region, but soil characteristics pose the challenges listed above. USDA-ARS is conducting research at a number of sites to develop aspirational cropping systems that attempt to simultaneously prevent or mitigate the losses of nutrients while preserving the production and profitability ecosystem services.

If IHTM capability existed, how could it be used to better address the problem(s)?
Some physical process modeling capability exists, and is being improved continually. Economic, societal, and other aspects could be added.

Potential Stakeholders:
Potential "Users" of IHTM Capabilities:
Potential "Developers" of IHTM Capabilities:

Scientific and Technical Challenges for IHTM Development:

Impact of IHTM capability to
- *Scientific:*

.
- *Societal*

Key Milestones:
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

Contact: John Sadler, USDA-ARS
john.sadler@usda.gov

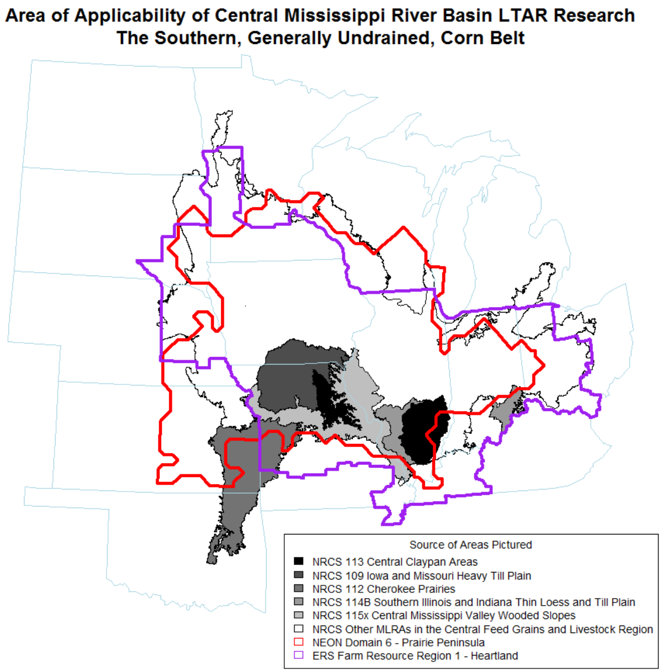
Use-Case for the Central Mississippi River Basin

Water-related Challenge(s):

- Surface soils in the region are permeable, but subsurface clay layers make drainage very slow
- Rapid saturation of the thin surface soil makes it prone to runoff, despite mild slopes, causing erosion
- Low profile water holding capacity makes the region susceptible to short-term water shortages
- Therefore, productivity and profitability are lower than elsewhere in the corn belt
- Losses of nutrients are somewhat lower, but loss of sediment and sometimes herbicides remain concerns

Context: The southern, undrained US Corn Belt is a moderately productive region, but soil characteristics pose the challenges listed above. No-till, cover crops, and some other practices successfully target some concerns, but actually exacerbate non-target concerns, particularly loss of surface-applied fertilizers and herbicides, and introduce others that may not have been recognized.

USDA-ARS is conducting research at the CMRB site to develop aspirational cropping systems that attempt to simultaneously address multiple ecosystem services. To date, win-win solutions have been elusive.



If IHTM capability existed, how could it be used to better address the problem(s)?
Some physical process modeling capability exists, and is being improved continually. Integration of economic, societal, and other aspects is needed.

Potential Stakeholders:
Potential "Users" of IHTM Capabilities:
Potential "Developers" of IHTM Capabilities:

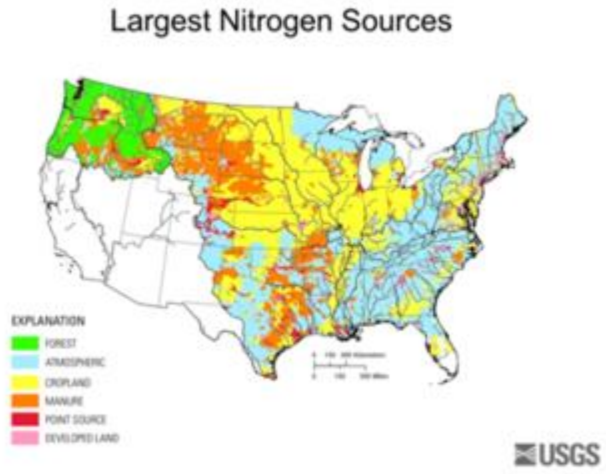
Scientific and Technical Challenges for IHTM Development:

Impact of IHTM capability to
- *Scientific:*
- *Societal*

Key Milestones:
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

Contact: John Sadler, USDA-ARS
john.sadler@usda.gov

Nutrients and Gulf of Mexico Hypoxia



Scenario/Place: Mississippi River Basin and Gulf of Mexico

Problem: Nutrient loading from the Mississippi River Basin is a primary contributor to the annual hypoxic zone in the Gulf of Mexico. Models linking river flux to hypoxic zone formation need to be improved.

Potential Stakeholders and Customers: State and local agencies, interagency Hypoxia Task Force, agricultural interest groups, NGOs

IHTM Role: Integration of coastal and river nutrient models allows for identification of optimal solutions to reduce nutrient loading and hypoxic area.

IHTM Impacts:

- *Scientific:* Coupled models that integrate watershed drivers, riverine nutrient loading, and coastal hypoxia formation.
- *Societal:* Improved management of nutrients and Gulf hypoxia

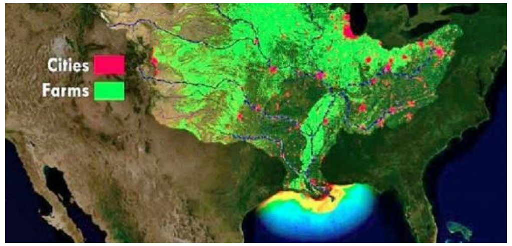
IHTM Needs:

- Accurately model nutrient sources, transport, and instream loads within the Mississippi River Basin on daily to annual time scales
- Improve predictions of hypoxic area in the Gulf by more accurately combining nutrient loading with other factors affecting hypoxia formation
- Support informed nutrient management in the Mississippi River Basin

Technical Barriers:

- Timely development of and access to model input data at fine spatial and temporal scales
- Standardized I/O
- Model coupling and validation

Potential IHTM "Developers": USGS, NOAA, USDA, EPA



Key Milestones:

Near-Term (0-2 yrs): Sub-annual riverine nutrient predictions and improved hypoxia forecasts
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational predictions to support management of climate and watershed nutrient drivers

POC(s):

- Lori Sprague, USGS, 303-236-6921, lsprague@usgs.gov
- TBD other agencies

Nutrients, Harmful Algal Blooms, and Toxic Algae

Scenario/Place: Conterminous US

Problem: Excess nutrients in inland rivers and lakes contribute to the formation of harmful algal blooms, which can cause hypoxic conditions and produce algal toxins that pose a threat to humans, wildlife, pets, and aquatic life.

Potential Stakeholders and Customers: Federal, state, and local agencies, the public (FWS, NPS)

IHTM Role: Integration of nutrient, temperature, and HABs models allows for near-real time forecasting and early warning of HABs outbreaks and identification of optimal solutions to reduce HABs formation.

IHTM Impacts:

- *Scientific:* Coupled models that integrate watershed drivers, climate, nutrient fate and transport, water temperature, and HABs formation (hypoxia, algal toxins)
- *Societal:* Improved ability to forecast HABs outbreaks and manage the causes of HABs formation and response to outbreaks

IHTM Needs:

- Accurately model temperature and nutrients, on daily time scales
- Improve predictions and early warning of HABs formation by better representation of multiple causative factors

Technical Barriers:

- Process understanding of factors affecting HABs formation in different parts of the United States
- Timely development of and access to model input data at fine spatial and temporal scales
- Model coupling and validation at a regional or national scale

Potential IHTM "Developers": USGS, NASA, NOAA, EPA, USACOE, USDA

Key Milestones:

Near-Term (0-2 yrs): Daily temperature and nutrient predictions, improved near-real time HABs forecasts, better leveraging of federal resources

Mid-Term (2-5 yrs): tightly coupled framework

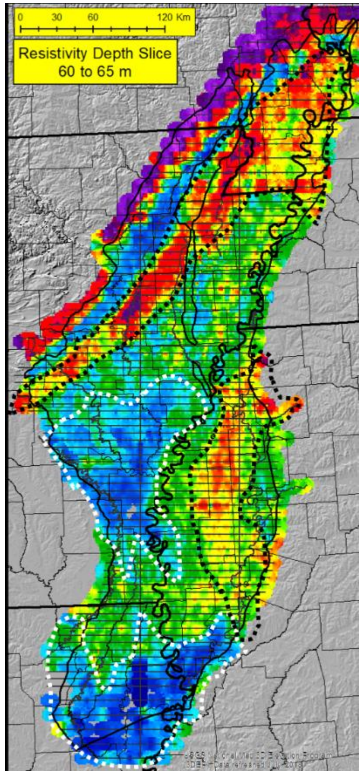
Long-Term (5-10 yrs): operational predictions to support near-real time forecasts of HABs outbreaks

POC(s):

- Jennifer Graham, USGS, 518-285-5706, jlgraham@usgs.gov
- Lori Sprague, USGS, 303-236-6921, lsprague@usgs.gov
- TBD other agencies

Integration of Surface and Subsurface Hydrologic and Hydraulic Models

Scenario/Place: US Lower Mississippi River Basin
Problem: Nutrient and sediment loadings are leading to hypoxic conditions. Intensive irrigation in row-crop agriculture is resulting in overdraft of the MRVAA. Models are not fully integrated.
Potential Stakeholders: State and local agencies, agricultural producers and agricultural industry, and other Federal agencies
IHTM Role: Integration of hydraulic and hydrologic models allows for identification of optimal solutions for quantity and quality of water resources, and ecosystem integrity.
Potential IHTM Customers: USEPA, USGS, USDA-NRCS, and State and local agencies.



IHTM Impacts:
- *Scientific:* Coupled models integrating watershed surface and subsurface runoff may help optimize the system for coordinated objectives
- *Societal:* Reduced water use and runoff will protect fragile ecosystems and enhance the sustainability of water resources
- *USDA-ARS Mission:* Long term sustainability of agro-ecosystems in the Lower Mississippi River Basin

IHTM Needs:
- Make information comprehensible and accessible
- Accurately represent combined effects from runoff and subsurface overdraft due to irrigation management
- Ability to run many complex and long data series
- Seamlessly couple/develop various model components and data types

Technical Barriers:
- Parallelization and optimization of coupled codes
- Standardized I/O
- Model coupling and validation,
- Iterative modeling capabilities

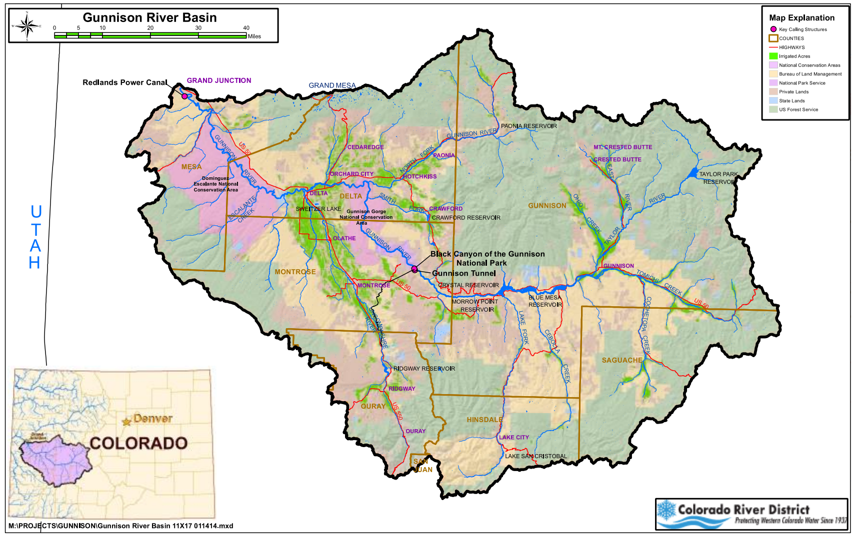
Potential IHTM "Developers": USDA, USGS, USEPA, USACE, NOAA

Key Milestones:
- Near-Term (0-2 yrs): Off-line, loose coupling of RUSLE2/AnnAGNPS/CONCEPTS surface & MODFLOW subsurface runoff models
- Mid-Term (2-5 yrs): tightly coupled framework
- Long-Term (5-10 yrs): operational framework integrated with Mississippi Embayment Regional Aquifer System (MERAS)

USDA POC(s):

- Martin Locke, USDA-ARS-NSL, 662.232.2908, Martin.Locke@usda.gov
- Ronald Bingner, USDA-ARS-NSL, 662.232.2966, Ron.Bingner@usda.gov
- Eddy Langendoen, USDA-ARS-NSL, 662.232.2924, Eddy.Langendoen@usda.gov

Gunnison River Basin Use Case



Water-related Challenge(s):

- Water resources in the heavily regulated Gunnison River system are a critical component of water deliveries from the Upper Colorado River Basin states in meeting obligations of the CO River Compact.
- Salinization and degraded water quality (selenium, heavy metals) from irrigation practices and natural geologic sources, as well as historic mining in the basin.
- Future impacts to snowpack accumulation and melt are key unknows affecting water deliveries.

Context: The Gunnison River basin contributes over 40% of stream flow to the Colorado River as it enters Utah and features some of the largest water storage infrastructure and Federal water rights in the Upper Colorado River Basin. The river is managed for water supply and quality, power generation, recreation, and endangered species recovery, with these management objectives often in conflict.

If IHTM capability existed, how could it be used to better address the problem(s)?
An IHTM capability would enable an integrated assessment of water availability and quality for a multi-faceted stakeholder base that enables a predictive capacity to better ameliorate the consequences of climate-driven changes in flows of water, nutrients, and metals.

Stakeholders: USBR, Colorado and Upper Basin states (WY, UT, NM), regional and local water conservancy districts
Potential "Users" of IHTM Capabilities: USGS WSCs, DOE, USBR, Colorado River District, Colorado Water Conservation Board
Potential "Developers" of IHTM Capabilities: USGS WMA, USGS WSCs, DOE, NOAA

Scientific and Technical Challenges for IHTM Development: Assimilation of watershed-to-basin scale datasets into predictive numerical models describing flows of water and energy in the Anthropocene; coupling to reactive transport models describing the flows of solutes controlling salinity and aqueous metals, such as selenium.

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate snowpack and melt/runoff timing, reservoir operations, ecosystem and human needs for water.
- *Societal:* Providing a framework for implementing a drought contingency plan for the Upper Colorado River basin state to meet Compact obligations.

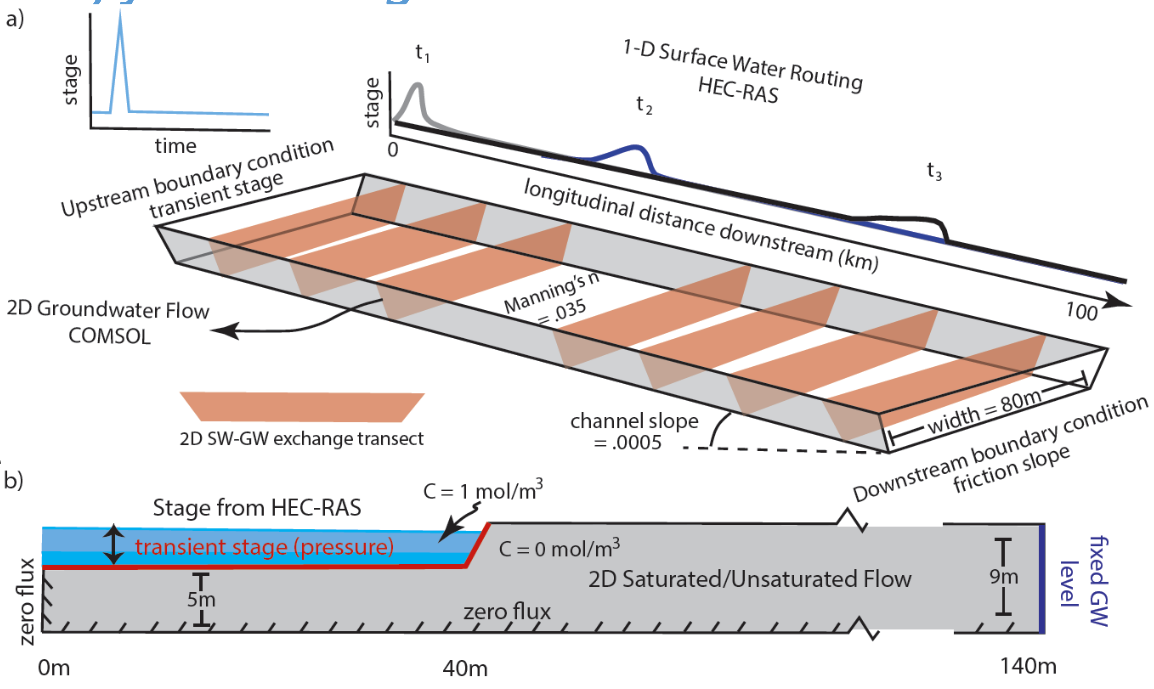
Key Milestones:
Near-Term (0-2 yrs): Coupling of multiple SW-GW models
Mid-Term (2-5 yrs): Integration of reactive transport capability
Long-Term (5-10 yrs): Operational system that allows for integration of multiple stakeholders (reservoirs, irrigators)

Contact: Ken Williams – Lawrence Berkeley National Lab
khwilliams@lbl.gov

Linked longitudinal (instream) and lateral (groundwater) flows in regulated river corridors

Water-related Challenge(s):
- Most large rivers are regulated by dams and other structures.
- River regulation determines downstream hydrology and chemistry.

Context: Coupled flow and transport in regulated rivers.



If IHTM capability existed, how could it be used to better address the proble
IHTM capacity would allow for real-time calculation of the downstream impact of river regulation on both rivers and aquifers.

Potential Stakeholders: Anyone interested in regulated rivers
Potential "Users" of IHTM Capabilities: USGS, NOAA, EPA, DOE
Potential "Developers" of IHTM Capabilities: USGS, NOAA, EPA, DOE
Scientific and Technical Challenges for IHTM Development: Parametrization of relevant processes and integration of river routing and groundwater flow models. Data assimilation and calibration.

Impact of IHTM capability to
- *Scientific:* Coupled models that integrate river routing, water quality and solute transport and novel but relevant processes.
- *Societal:* Understand consequences of river regulation.

Key Milestones:
Near-Term (0-2 yrs): Off-line, integration of routing and transport
Mid-Term (2-5 yrs): tightly coupled framework and addition of relevant processes (river corridor exchanges)
Long-Term (5-10 yrs): operational system that accounts for all processes, dynamics, and varying boundary conditions

Stephen Ferencz (Univ. of Texas at Austin): stephenferencz@gmail.com
Bayani Cardenas (Univ. of Texas at Austin): cardenas@jsg.utexas.edu
Bethany Neilson (Utah State Univ.): bethany.neilson@usu.edu

Integration of National Water Model (NWM) and Hydrologic and Water Quality System (HAWQS)

Challenge: Excess nutrient loading in the Mississippi Basin, Great Lakes, and other areas resulting in hypoxia, algal blooms and HABs

- Drinking water sources shut down and treatment costs increased
- People and wildlife sickened, fish killed, recreation and fisheries affected.

Context: Accurate prediction of hypoxia, algal blooms, and HAB formation could provide time for water managers to:

- Limit irrigation pumping and point source discharges
- Adjust intakes to water treatment plants and prepare for enhanced treatment
- Close recreation areas and fisheries to prevent injury from contaminated water.

How would improved IHTM capability enhance our ability to address problems?

- Provide early warning and real time forecasts of hypoxia, excess algal blooms and HABs
- Provide long-term prediction of precipitation, stream flows and water quality required to design infrastructure and mitigation strategies
- Provide input to cost-benefit and policy analyses by local, state, and national organizations charged with developing infrastructure and policies to limit the occurrence and impacts of hypoxia, excess algal blooms and HABs.

If IHTM capability existed, how would it impact and benefit society: Help water resource managers and policy makers design and implement policies and practices needed to reduce the incidence and decrease the impacts of hypoxia, excess algal blooms and HABs.

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): Water Resource Managers, Water Policy Managers
Potential "Users"/"Operators" of IHTM Capabilities: EPA, States
Potential "Developers" of IHTM Capabilities: EPA, TAMU, NOAA

Scientific and Technical Challenges for IHTM Development: Improved communication between the NOAA-USGS Nation Water Model team with the EPA-USDA HAWQS model team

- The Spatial and Temporal resolution of the two models are different, and processes are different, so a careful coordination of the algorithms, inputs at spatial and temporal scale along with handling the voluminous of data and parallelization will be of high challenge.
- Financial and human resources needed to coordinate and integrate interactions and user tools of the integrated NWM-HAWQS toolkit
- Development of model documentation, training materials, and advisory and user groups needed to launch the integrated system.

Opportunity for IHTM development based on this specific use-case

- Better integration of existing development teams and capabilities of NWM and HAWQS
- Development of new capabilities to predict, manage, and mitigate the effects of hypoxia, excess algal blooms and HABs.

Key Milestones and Phased Development:

Near-term (0-2 yrs): HAWQS data updates and user interface improvements
Mid-term (2-5 yrs.): Coordinate temporal and spatial scales; link NWM precipitation to HAWQS
Long-term (5-10 yrs.): link HAWQS runoff and water quality loadings to NWM

Joel Corona, U.S. EPA, corona.joel@epa.gov
Rajbir Parmar, U.S. EPA, parmar.rajbir@epa.gov
Raghavan Srinivasan, Texas A&M University, r-srinivasan@tamu.edu
Steve Whitlock, U.S. EPA, whitlock.steve@epa.gov

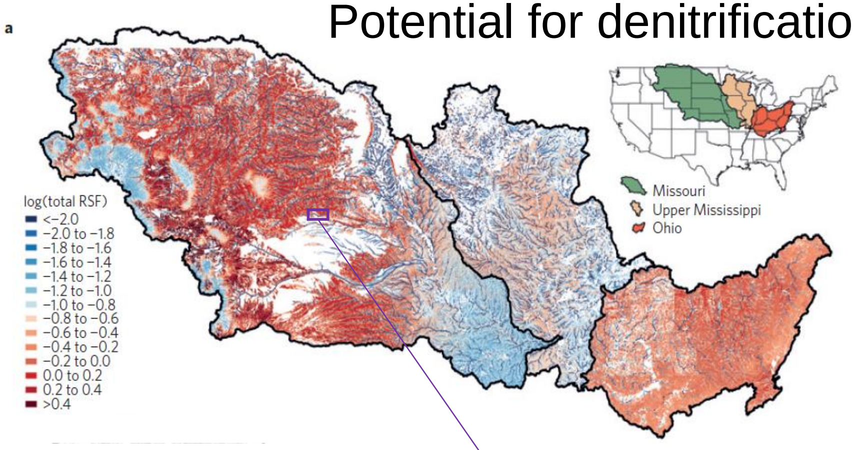
Mississippi River Basin water quality (N) modeling with river corridor exchanges

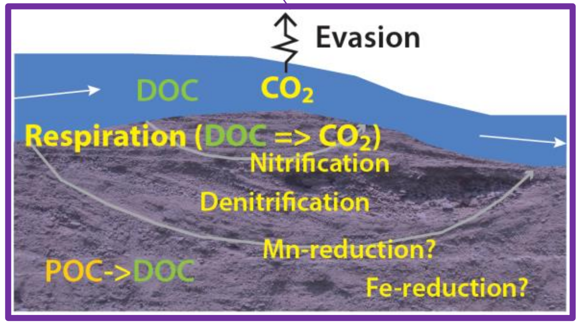
Water-related Challenge(s):

- The MRB is eutrophic due to nutrient inputs from land.
- Some of this input which originates from land, enters the river and ultimately, infiltrates into the sediment and undergoes reactions, e.g., denitrification. What reactions take place and how much they occur determines the buffering capacity of the river.
- N loading will not abate soon, and hence understanding this buffering is critical.

Context: The water quality of the MRB is crucial not only to all users of Mississippi River water and the environment. It also determines the extent of the deadzone in the Gulf of Mexico.

Potential for denitrification





If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for real-time calculation of where and when the potentially beneficial reactions happen and whether it happens are sufficient rates to impact water quality downstream.

Potential Stakeholders: States and cities within the MRB; states in the Gulf of Mexico
Potential "Users" of IHTM Capabilities: USGS, NOAA, EPA, DOE, state env. quality departments and river authorities,
Potential "Developers" of IHTM Capabilities: USGS, NOAA, EPA, DOE
Scientific and Technical Challenges for IHTM Development: Parametrization of relevant processes and integration with river water quality and routing models. Model inputs such as reaction kinetics, and concentrations of solutes of interest.

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate river routing, water quality and solute transport and novel but relevant processes.
- *Societal:* Understand the risk and vulnerability of the MRB to nutrient pollution.

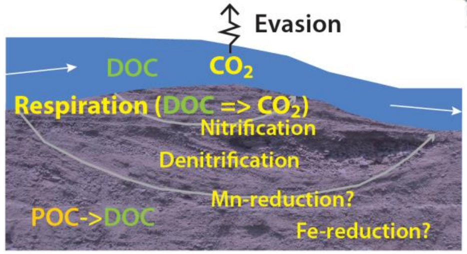
Key Milestones:
Near-Term (0-2 yrs): Off-line, integration of routing and transport
Mid-Term (2-5 yrs): tightly coupled framework and addition of relevant processes (river corridor exchanges)
Long-Term (5-10 yrs): operational system that accounts for all processes, dynamics, and varying boundary conditions

Jesus Gomez-Velez (Vanderbilt Univ.): jesus.gomezvelez@vanderbilt.edu
Bayani Cardenas (Univ. of Texas at Austin): cardenas@jsg.utexas.edu

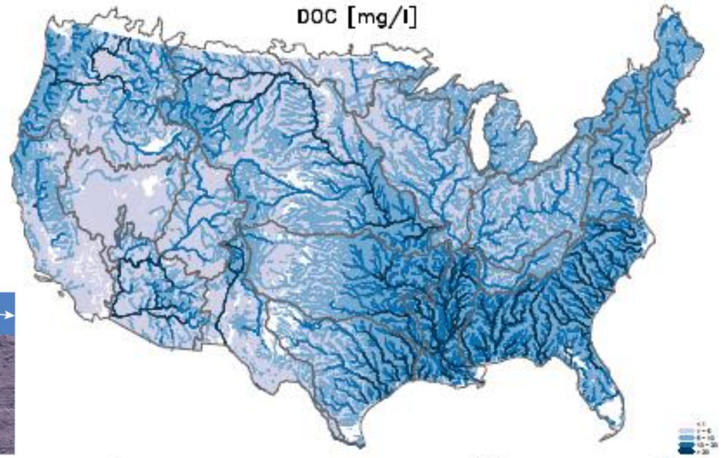
Carbon cycling by river corridors of the CONUS

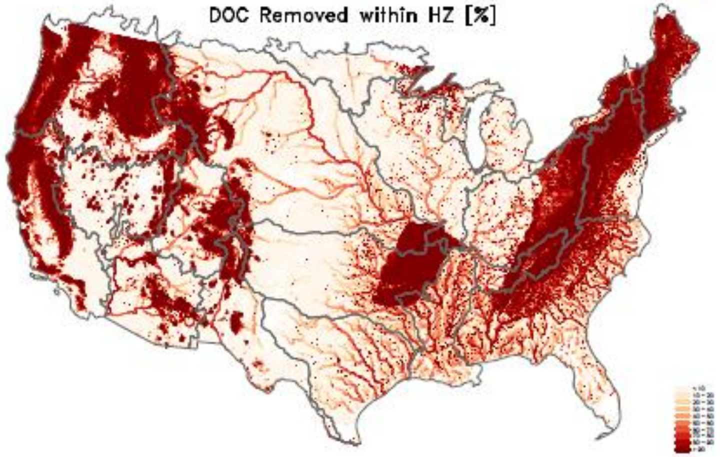
Water-related Challenge(s):

- Carbon budgets of watersheds are hard to calculate and include surface-subsurface exchanges.
- River sediment can buffer nutrients and carbon but the reactions produce greenhouse gases.



Context: Carbon cycling and carbon budgets of watersheds and river networks.





If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for real-time calculation of carbon cycling.

Potential Stakeholders: Anyone interested in large-scale C accounting
Potential "Users" of IHTM Capabilities: USGS, NOAA, EPA, DOE
Potential "Developers" of IHTM Capabilities: USGS, NOAA, EPA, DOE
Scientific and Technical Challenges for IHTM Development: Parametrization of relevant processes and integration with river water quality and routing models. Model inputs such as reaction kinetics, and concentrations of solutes of interest. Data assimilation

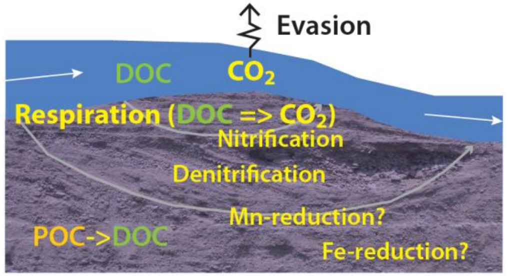
Impact of IHTM capability to

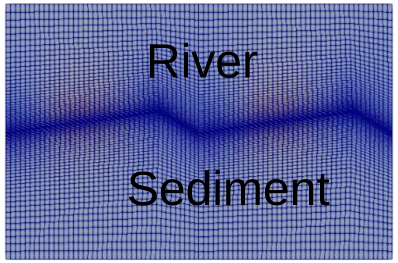
- *Scientific:* Coupled models that integrate river routing, water quality and solute transport and novel but relevant processes.
- *Societal:* Understand carbon budgets.

Jesus Gomez-Velez (Vanderbilt Univ.): jesus.gomezvelez@vanderbilt.edu
Bayani Cardenas (Univ. of Texas at Austin): cardenas@jsg.utexas.edu
Xingyuan Chen (Pacific Northwest Natl. Lab): xingyuan.chen@pnnl.gov

Key Milestones:
Near-Term (0-2 yrs): Off-line, integration of routing and transport
Mid-Term (2-5 yrs): tightly coupled framework and addition of relevant processes (river corridor exchanges)
Long-Term (5-10 yrs): operational system that accounts for all processes, dynamics, and varying boundary conditions

Fully coupled modeling of river corridors (i.e., including riparian, parafluvial, and hyporheic zones)

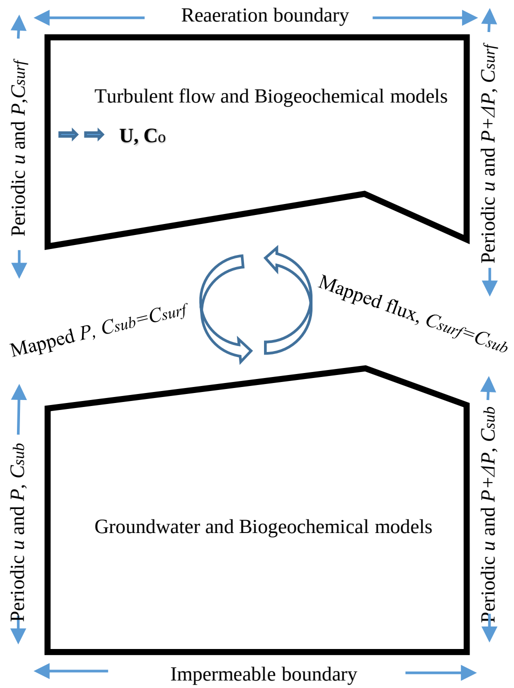




Water-related Challenge(s):

- Water moves in and out of the surface and subsurface- these form a continuum.
- Water quality in rivers and aquifers depends on connectivity.
- Flow and transport models usually treat surface and subsurface waters independently.

Context: All river water enters the sediment comprising river banks and beds, and reactions take place in the sediment that normally do not occur in the river or that occur at much smaller rates.



If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for prediction of which processes matter most for water quality across river corridors.

Potential Stakeholders: USGS, EPA, DOE
Potential "Users" of IHTM Capabilities: USGS, EPA, DOE
Potential "Developers" of IHTM Capabilities: USGS, EPA, DOE
Scientific and Technical Challenges for IHTM Development: Numerical issues (convergence, stability), computational resources, reconciliation of disparate time and spatial scales

Impact of IHTM capability to

- *Scientific:* Coupled mechanistic models that consider surface and subsurface waters as a continuum
- *Societal:* Understand which processes can be targeted by management for pollution reduction.

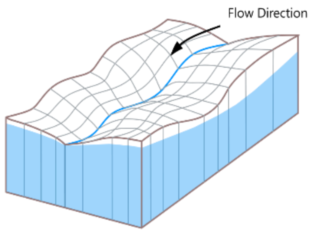
Key Milestones:
Near-Term (0-2 yrs): Off-line, integration of processes
Mid-Term (2-5 yrs): tightly coupled framework and addition of relevant processes
Long-Term (5-10 yrs): operational use is unlikely except for relatively small domains (perhaps hundreds of meters)

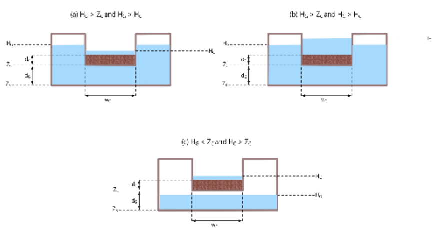
Xiaofeng Liu (Penn. State. Univ.): xliu@engr.psu.edu
Bayani Cardenas (Univ. of Texas at Austin): cardenas@jsg.utexas.edu
Xingyuan Chen (Pacific Northwest Natl. Lab.): Xingyuan.Chen@pnnl.gov

Assessing surface-groundwater flows in regulated rivers using component-based models

Water-related Challenge(s):

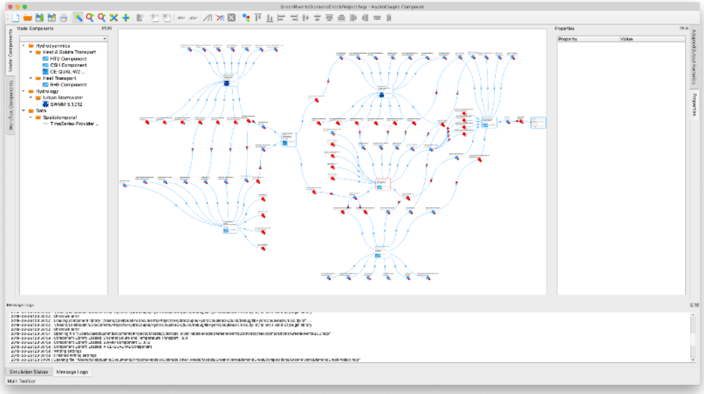
- Large rivers regulated by dams and other structures induce surface-groundwater exchanges that occur across a hierarchy of scales
- What are the magnitudes of these exchanges and their short and long term effects on stream and groundwater quality and how do changing reservoir conditions affect these impacts?





Context: Multi-scale coupled flow and transport in regulated rivers using component-based models

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for using scale appropriate transport formulations for different parts of the system to balance degree of fidelity with computational costs



Potential Stakeholders: Anyone interested in regulated rivers and reservoirs and impacts of surface-groundwater exchanges on hydrology and biogeochemistry
Potential “Users” of IHTM Capabilities: USGS, NOAA, EPA, USBR, DOE
Potential “Developers” of IHTM Capabilities: USGS, NOAA, EPA, USBR, DOE

Scientific and Technical Challenges for IHTM Development: Efficient and conservative handling of feedbacks at boundaries, parallelization and optimization of model codes, converting existing codebases into framework compliant components

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate reservoir response and operations, river routing, and solute transport at relevant scales
- *Societal:* Understand the consequences of repeated dam releases on water quality and various riverine ecosystems

Caleb Buahin (Utah State Univ.): caleb.buahin@usu.edu
Bethany Neilson (Utah State Univ.): bethany.neilson@usu.edu
Bayani Cardenas (Univ. of Texas at Austin): cardenas@jg.utexas.edu
Stephen Ferencz (Univ. of Texas at Austin): stephenferencz@gmail.com

Key Milestones:
Near-Term (0-2 yrs): Suite of framework compliant multi-scale surface and groundwater model components
Mid-Term (2-5 yrs): A community of model developers and users who continually advance and improve models
Long-Term (5-10 yrs): Operational system that accounts for all relevant processes, dynamics, and boundary conditions

In- and Near-Field Modeling and Data Needs for Effective Nutrient Management

Water-related challenge(s):

- While many types of sources may contribute to excess nutrients in surface water, agriculture is a large source in areas such as the Mississippi River-Atchafalaya River Basin (MARB) and Western Lake Erie Basin (WLEB).
- Effectively using limited conservation dollars to reduce nutrient losses from agriculture requires models that represent how various conservation practices and systems can avoid, control and trap nutrient movement from fields through multiple pathways into waterways.
- To predict conservation practice and system effectiveness, these models need to be parameterized with robust datasets on emerging, innovative, high-impact conservation practices, and how these practices interact in systems of practices to reduce nutrient losses. Pre- and post-implementation monitoring datasets are needed to validate model parameterization and calibration.
- Without these high-resolution models and datasets, water quality and conservation program managers are challenged to most effectively use scarce resources to reduce nutrient losses that can contribute to local, near-field and far-field hypoxia and HAB events.

Context: In the MARB, 12 states and five federal agencies are working collaboratively in a "Hypoxia Task Force" to reduce nutrient losses that contribute to a large hypoxic zone in the Northern Gulf of Mexico. Analyses by an EPA Science Advisory Board and more recently by NOAA show that reductions in nutrient and phosphorus loads of about 45 percent are needed to meet the Task Force's Goal for reducing the hypoxic zone. In the WLEB, phosphorus reductions of 40 percent are needed to meet U.S. commitments in the U.S.-Canada Great Lakes Water Quality Agreement, with most of these reductions needed in the Maumee River Basin. Achieving these levels of reductions on a subcontinent- or major river basin-scale is not possible without highly effective use of conservation dollars at the field and sub-field scale.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? IHTM that incorporates field and sub-field scale models, supported by robust data sets, could help ensure that conservation investments are used as effectively as possible to reduce the extent, duration and severity of hypoxia and HAB events. More complete information on the placement of conservation practices and systems on the landscape can help improve the capabilities of water quality models to predict nutrient loads and correlate these loads to hypoxia and HAB events.

If IHTM capability existed, how would it impact and benefit:

Society: Fewer, less frequent and less severe hypoxic and HAB events that cause ecological damage, endanger human health and can have large economic consequences.

Science: Improved capability to manage scarce conservation resources to ensure maximum return on these investments. Improved capability of water quality models to predict how conservation investments will improve water quality, and further optimize the placement of conservation treatments for maximum reduction of hypoxic zones and HABs.

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): State water resource and water quality agencies, conservation districts, and water providers.
Potential "Users"/"Operators" of IHTM Capabilities: USDA, state water resource agencies, USGS, and EPA
Potential "Developers" of IHTM Capabilities: USDA, USGS, Academia, States, NASA, DOE, and EPA

Tom Wall, U.S. EPA
Office of Water,
202-564-4179

Scientific and Technical Challenges for IHTM Development: The challenge is primarily one of financial and technical resources. Some scientific and technical challenges in improving optical analysis of LIDAR/satellite/aerial imagery and machine-based reading of these imagery.

Opportunity for IHTM development based on this specific use-case 1) Better integration of existing capabilities: Integrate newly developed tools for analyzing LIDAR/satellite/aerial imagery for documenting conservation tillage, cover cropping and structural conservation practices into models that predict nutrient loads at various landscape scales; 2) Development of new capabilities: Work in public-private partnerships to develop robust,accurate machine-based tools for analyzing LIDAR/satellite/aerial imagery to document placement of conservation practices and systems on the landscape.

Key Milestones and Phased Development:

- Near-Term (0-2 yrs): Expanded LIDAR datasets and datasets on the effectiveness of emerging conservation practices (e.g., saturated buffers); state-scale calibration of existing models; completion of key elements in SWAT+ development; continued development of tools, including machine-based learning approaches, to analyze LIDAR/aerial and satellite imagery to determine optimal placement of conservation tillage, cover cropping and structural conservation systems across major basins and watersheds.
- Mid-Term (2-5 yrs): Continue/build upon near-term work. Use near-term work to better calibrate larger-scale water quality models and ID optimal locations for additional conservation investments
- Long-Term (5-10 yrs): Continue/build upon near- and mid-term work.

International Basins

Water-related challenge(s): Water management and planning require modeling tools that represent basin hydrologic processes with confidence

Context: In transboundary watersheds, forcing and parameter estimation datasets may stop or experience marked differences at political boundaries.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? IHTM could facilitate collaboration between communities contributing datasets and methods used in modeling that support water management and planning. Awareness of how data may be used in the IHTM context, particularly in transboundary regions, could lead to more useful data development.

If IHTM capability existed, how would it impact and benefit:

Society: Better estimates of water availability in the future will facilitate improved societal outcomes (e.g. drought preparedness / resiliency)

s

Science: Datasets developed with hydrologic applications in mind will lead to more consistent, efficient modeling in transboundary regions.

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): Water users and natural resource managers
Potential “Users”/”Operators” of IHTM Capabilities: Reclamation, USACE, other water management / planning entities
Potential “Developers” of IHTM Capabilities: NOAA, USGS, Universities

Scientific and Technical Challenges for IHTM Development: monitoring networks and historical data may be limited in these regions or may not be easily accessed

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities:

Development of new capabilities:

Phased Approach to Development:

Near-Term (0-2 yrs): Identify geographic domain for IHTM

Mid-Term (2-5 yrs): Establish standards for new datasets and revise existing datasets to IHTM domain

Long-Term (5-10 yrs): Update and maintain data

Contact:

Ken Nowak
knowak@usbr.gov

Multi-Objective IHTM Modeling: Non-Climate Factors

Scenario/Place: Integrated weather & water based impact predictions
Problem: Models for predicting hydrologic outcomes are not integrated with other systems (i.e. reservoir management, waterway transportation management, power generation, military readiness, etc) that can be significantly impacted by weather/hydrology, and vice versa.
Potential Stakeholders: USACE, NOAA, Bureau of Rec, DOE…
IHTM Role: Potential for optimizing complex systems with respect to both climatic and non-climatic objectives.
Potential IHTM Customers: Federal, State, Municipal, Industry, Ag
IHTM Impacts:

- *Scientific:* New multi-objective, risk-based decision support systems that simultaneously balance climatic and non-climatic hydrologic risks to infrastructure a real-time or near real-time basis.
- *Societal:* Improved economy and environment, disaster preparation.
- *USACE Mission:* Reduced secondary and tertiary impacts of hydrologic control decisions.

IHTM Needs:

- **Fully linked hydrologic predictions (weather through streamflow)**
- **Integrated water predictions with decision support systems**
- **Multi-agency program to support capability development**

Technical Barriers:

- **Challenges with the accuracy of a fully integrated system**
- **Multi-disciplinary/multi-agency collaborations difficult**
- **How to accurately characterize uncertainty within a "system of systems" and use it to predict infrastructure risk**

Potential IHTM "Developers": NOAA/USACE/DOE

Key Milestones:

Near-Term (0-2 yrs): TBD
Mid-Term (2-5 yrs): TBD
Long-Term (5-10 yrs): TBD

USACE POC(s):

- John Eylander, 603.646.4188, John.B.Eylander@usace.army.mil
- Mark Wahl, 937.255.8309, Mark.D.Wahl@usace.army.mil

Water Resource Allocations and Planning

Scenario/Place: Tuolumne River System
Problem: Multiple stakeholders seek water allocations from finite sources, resulting in potential conflicts during times of water stress.
Potential Stakeholders: Communities, States, Industry, Agriculture
IHTM Role: Integration of hydraulic models, reservoir operation / irrigation models, ecosystem models, many scenarios of long meteorological time series, and hydrologic models across agencies could allow integrated solutions to enhance resilience to both droughts and floods.
Potential IHTM Customers: DOI, USACE, FEMA, DOE, DOI, EPA, State Water and Environmental Agencies, and local Irrigation districts and utilities
IHTM Impacts:

- *Scientific:* New water resource allocation models that simultaneously consider geographic, environmental, and economic factors.
- *Societal:* Coordinated tools to enhance resilience to droughts and floods.
- *USACE mission*:

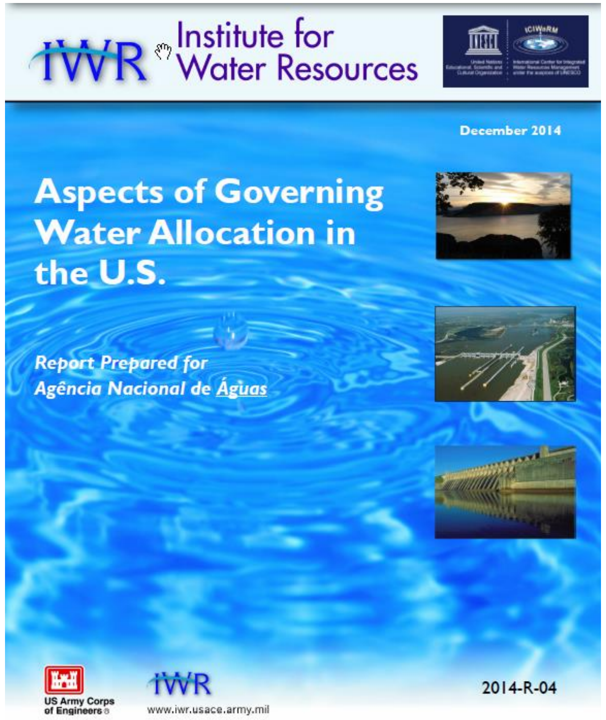
IHTM Needs:

- Ability to run many complex and long data series
- Seamlessly couple/develop various model components and data types
- Flexibility to transfer output and visualize key information of interest by different stakeholders

Technical Barriers:

- Computational power for model large data sets
- Iterative modeling capabilities
- Certification of models
- Managing different modelling time-scales

Potential IHTM "Developers": USACE, CADWR, USBR



Key Milestones:

Near-Term (0-2 yrs):TBD
Mid-Term (2-5 yrs):TBD
Long-Term (5-10 yrs): TBD

USACE POC(s):

Guillermo Mendoza, IWR, (703)428-6137, Guillermo.f.Mendoza@usace.army.mil

Western U.S. water management for multi sector analyses

Water-related challenge(s): understand the water availability conditions that define and support the prediction of normal, outside of normal and vulnerability dynamics in the energy and land use sectors, and how those conditions feed back into water dynamics.

Context: The electricity sector relies on water-dependent technologies to generate power and provide reserve services that support the reliability of the system. The coupling of water and energy systems showed that specific drought patterns could lead to beyond normal operations and that those tipping point conditions could be predicted. Land use also relies on water availability to ensure reliable system. A range of other models exist for water and land use systems .

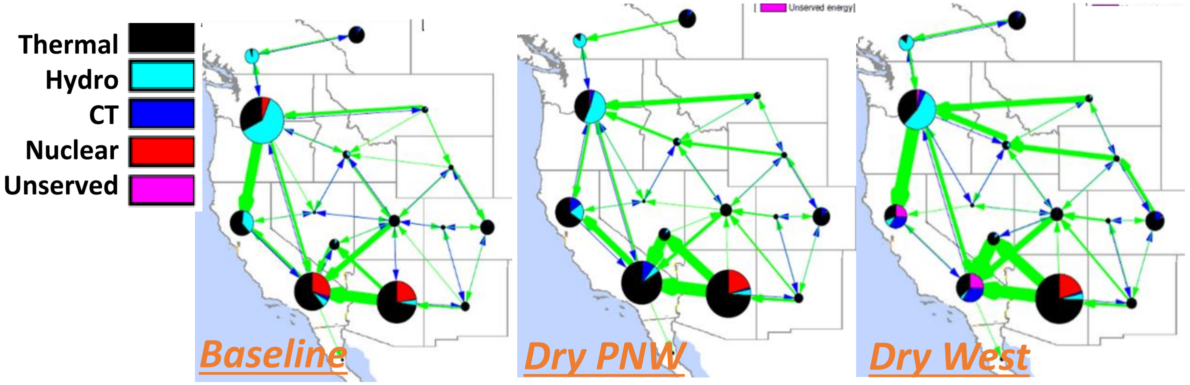
If IHTM capability existed, how would it enhance our ability to address the problem(s)?
The capability would enhance the development of national datasets -which would increase the value of the investment, provide consistency in the science and conclusions, and most important unlock the research on the co-evolution of water and energy systems at the regional scale and understand the boundaries of normal conditions dynamics, beyond normal conditions and tipping point for new dynamics .

If IHTM capability existed, how would it impact and benefit:
Society: provide a more robust science to support decision-making
Science: understand and quantify the equilibrium boundaries for water resources managers and stakeholders to guide water management and support sector specific water uses or interactions.

DOE, Multi-Sector Dynamics program area

Specific drought patterns drive to higher vulnerability

Regional generation portfolio and transmission



Potential Stakeholders : CAISO, WECC, Reclamation, States, USGS, EPA, DOE
Potential “Users”/”Operators” of IHTM Capabilities: DOE, Reclamation, NOAA
Potential “Developers” of IHTM Capabilities: DOE, Reclamation, USGS, USGS, NSF, NOAA

Scientific and Technical Challenges for IHTM Development:
- Different governances for water, land use and energy, and across scales
- Inconsistent or lack of coincident sectoral data
- Surface water and groundwater use and allocations/emerging management
- Earth and Human system models developed in silo with inconsistent representation and/or underlying assumptions

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: <need to harmonize capabilities with other agencies>
Development of new capabilities: <harmonize assumptions, develop datasets, new couplings>

Phased Approach to Development: TBD as a team
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

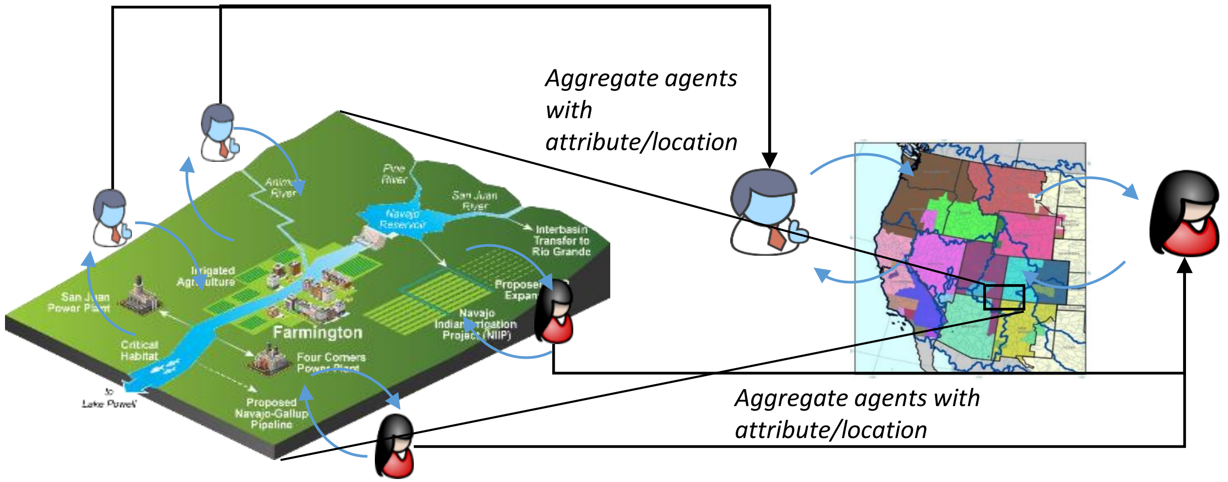
San Juan watershed - management for multi sector analyses

Water-related challenge(s): Water management in the San Juan River Basin provides to agriculture and energy sector locally, and water demands outside of the basin. The water allocation is highly regulated by institutions yet over different spatial and temporal scales. What are the inter-actions between sectors that can help define the normal sectoral operations, and trade offs, see new equilibrium, when exposed to external and internal stressors such as economics, institutions and water availability?

Context: The electricity sector relies on water-dependent technologies to generate power and provide reserve services that support the reliability of the system. Agriculture relies on predictable water supply to define the reliability – revenue of the system. The allocation of water is influenced by institutions that define other stakeholders.

If IHTM capability existed, how would it enhance our ability to address the problem(s)?
The capability would enhance the understanding of interactions between water users and managers across scales and better predict how the spatial resolution and complexity of "agents" can influence the definition of normal and beyond normal operations.

If IHTM capability existed, how would it impact and benefit:
Society: provide a more robust science to support decision-making
Science: understand and quantify the equilibrium boundaries for water resources managers and stakeholders to guide water management and support sector specific water uses or interactions.



Potential Stakeholders : Tribes, Reclamation, power utilities, farmers
Potential "Users"/"Operators" of IHTM Capabilities: DOE, Reclamation
Potential "Developers" of IHTM Capabilities: DOE, DOI, USGS, NOAA, NSF

Scientific and Technical Challenges for IHTM Development:
- Different governances for different sectors,
- Inconsistent or lack of data
- External forcing
- Local models developed in silo with respect to more regional models

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: <need to harmonize capabilities with other agencies>
Development of new capabilities: <harmonize assumptions, develop datasets, new couplings>

Phased Approach to Development:
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

DOE, Multi-Sector Dynamics program area

Groundwater Banking in the Western U.S.

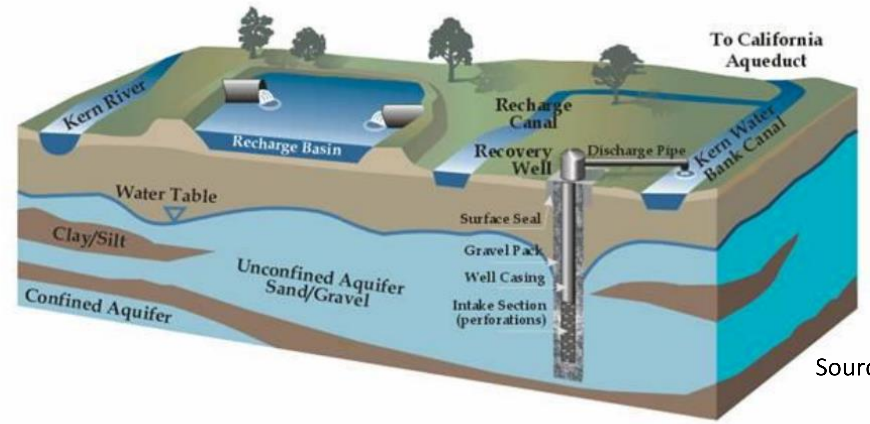
Water-related challenge(s): In light of declining mountain snowpack, there is increasing interest in investigations of groundwater banks for wintertime water storage throughout the western U.S. However, physical and bureaucratic difficulties make optimization of a comprehensive groundwater portfolio difficult.

Context: Mountain snowpack is one of the largest reservoirs for wintertime water storage, but annual mean snow water equivalent projected to decline throughout the U.S. West by 20-40% by mid-century. Groundwater banking, where underground aquifers are replenished in the winter season via controlled flooding, fallowing and injection wells, is currently being considered as an avenue to recover some of this lost storage capacity.

If IHTM capability existed, how would it enhance our ability to address the problem(s)?
The capability would enhance the development of national datasets where groundwater storage can be recorded and managed. Coordination with meteorological projections on seasonal timescales will enable water managers to develop targeted water management strategies.

If IHTM capability existed, how would it impact and benefit:
Society: improve drought resilience through increased water storage.
Science: understand issues related to the management and operation of groundwater banking in light of a changing climate.

DOE, Multi-Sector Dynamics program area



Source: Kern Water Bank 2010

Potential Stakeholders: Water management agencies, States, USGS, EPA, DOE
Potential "Users"/"Operators" of IHTM Capabilities: Water management agencies, States, USGS, EPA
Potential "Developers" of IHTM Capabilities: DOE, Reclamation, USGS, NSF, NOAA

Scientific and Technical Challenges for IHTM Development:
- Different governances for water, land use and energy, and across scales
- Inconsistent observational data of subsurface character and surface flows
- Surface water and groundwater use and allocations/emerging management

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: integration of water management models and integr
Development of new capabilities: <harmonize assumptions, develop datasets, new couplings>

Phased Approach to Development: TBD as a team
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

Natural / Virgin Flows

Water-related challenge(s): Water management and planning require modeling tools that represent basin hydrologic processes with confidence

Context: A lack of availability / consistency in natural/virgin flow data sets across the United States can make hydrologic model calibration difficult.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? Consistent, widely available natural/virgin flows would allow for greater model fidelity to natural process representation by not having calibration efforts convoluted by anthropogenic impacts in flow data.

If IHTM capability existed, how would it impact and benefit:

- Society: Improved models likely offer more accurate estimates of future water availability; this may facilitate improved societal outcomes (e.g. drought preparedness)
- Science: Robust natural flow data have a range of potential science benefits/applications beyond model calibration (e.g. assessments of historical trends in water availability).

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): water users (municipalities, growers, etc)
Potential "Users"/"Operators" of IHTM Capabilities: NOAA, Reclamation, USACE, other resource management agencies
Potential "Developers" of IHTM Capabilities: USGS, universities,

Scientific and Technical Challenges for IHTM Development: Data on diversions, depletions, regulation, and other anthropogenic impacts may not be readily available or of the desired timestep. These datasets must be maintained.

Opportunity for IHTM development based on this specific use-case

- Better integration of existing capabilities:
- Development of new capabilities:

Phased Approach to Development:

- Near-Term (0-2 yrs): Identify existing datasets and methods
- Mid-Term (2-5 yrs): Develop and deploy "standard" method to test basins
- Long-Term (5-10 yrs): CONUS deployment and updating

Bureau of Reclamation

Modeling Complex Groundwater Surface Water Interactions

Water-related challenge(s): Water management and planning require modeling tools that represent basin hydrologic processes with confidence

Context: Modeling tools for complex groundwater surface water interactions are important for long term water resources planning. In some regions, current tools are challenged by unique groundwater characteristics. Model output that differ significantly from observed data (e.g. modeled vs observed hydrograph) require significant bias correction, which may lessen confidence in results.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? Ideally, IHTM capability would increase the availability of interoperable models and model modules; this might offer a broader palette of components from which to address unique basin characteristics.

If IHTM capability existed, how would it impact and benefit:

Society: Better estimates of water availability in the future will facilitate improved societal outcomes (e.g. drought preparedness)

Science: Improved hydrologic process representation would allow resources to be devoted to other important topics

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): Water users and natural resource managers

Potential “Users”/”Operators” of IHTM Capabilities: Reclamation, USACE, other water management / planning entities

Potential “Developers” of IHTM Capabilities: NOAA, USGS, Universities

Scientific and Technical Challenges for IHTM Development: a bulleted list

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities:

Development of new capabilities:

Phased Approach to Development:

Near-Term (0-2 yrs): Develop/demonstrate model/model configurations for complex groundwater

Mid-Term (2-5 yrs): Couple groundwater model with surface water model and demonstrate for select basins

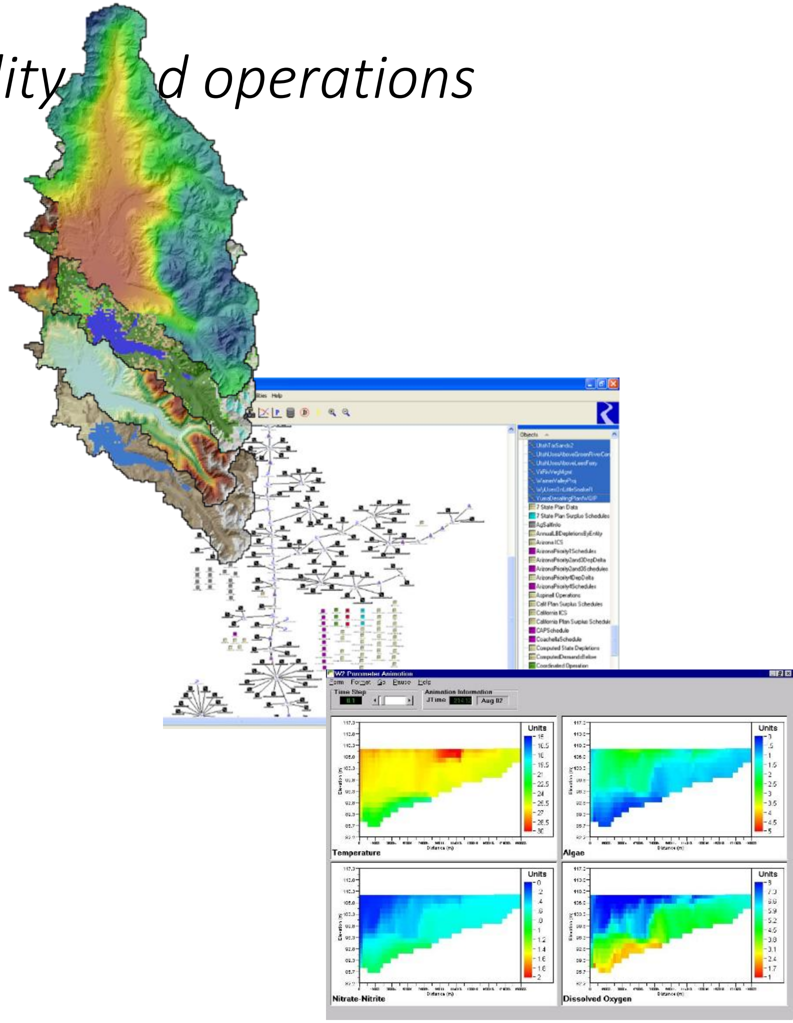
Long-Term (5-10 yrs): Make available coupled model with documentation, including configuration guidance

Contact:

Ken Nowak

knowak@usbr.gov

Integration of watershed hydrology, reservoir water quality and operations



Place: Grand Lake, CO; part of the Colorado Big Thompson Project

Problem(s): physically-based models of hydrology and water quality are used with an operations model to adaptively manage the Three Lakes System and the greater Colorado Big Thompson project. Both hydrology and operations impact the water quality in Grand Lake so operating this system optimally (for water deliveries and to meet water quality goals) requires a system that accounts for the feedbacks between operations, watershed hydrology, and water quality.

If IHTM capability existed, how could it be used to better address the problem(s)? Integrating these models (or providing a smooth path for running them together) in a real-time or forecasting application would provide needed information to better manage this system.

Potential Stakeholders: Reclamation, NPS, USFS, local governments and water providers
Potential "Users" of IHTM Capabilities: Reclamation
Potential "Developers" of IHTM Capabilities: Reclamation, others?

Scientific and Technical Challenges for IHTM Development:
- Computing demands for real time applications with multiple scenarios
- Model validation for stakeholder confidence
- Incorporating forecasting data

Impact of IHTM capability to
Society: Minimize water quality influence of operations while maintaining water deliveries
Science: Diverse processes requiring flexible framework

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities:
Development of new capabilities:

Phased Approach to Development:
Near-Term (0-2 yrs): Loose coupling
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs): Incorporation of forecasting

Bureau of Reclamation

Snow Modeling and Forecasting for the State of California

Water-related challenge(s):

- Merging modeling & remote sensing for water supply forecasting and flood warning
- Managing 100's of Tbytes of forcing data and model output per year
- Transition modeling & data from point (station & survey samples) to spatial

Place: California, Southern Sierra Nevada, 6 large basins (2019), 54000 km^2, @ 50 m resolution. This region typically generates more than 7,000,000 Acre-feet of rainfall & snowmelt, which provides nearly 33% California's agricultural water supply.

Primary Stakeholders: CA Department of Water Resources, USDA-NRCS, USBR, Kings River Water Association, San Francisco PUC, Turlock Irrigation District, Friant Water Authority, Merced Irrigation District, Kaweah Delta Water District, Mammoth Community Water District

If IHTM capability existed, how could it be used to better address existing challenges? IHTM capacity would allow development of coupled streamflow modeling and facilitate the testing of utilities for creating a spatial data repository tool kit for managing, accessing, and reformatting extracted information from very large spatial data sets so that these data could be used by modeling efforts across a wide range of disciplines.

Scientific and Technical Challenges for IHTM Development:

- Spatial data access for model input and validation
- Models written and developed for very different applications will be difficult to standardize and couple

Shasta Lake, 2014 & 2015

Oroville Dam Spillway, March 3, 2017

Impact of IHTM Capability:

Scientific: The development of an IHTM data repository expand the access to large data sets such that a much wider range of hydrologic and environmental models would be able to utilize it.

Societal: Allow water and resource managers to access very large data sets for improved resource management decisions.

Key Milestones:

- Near-Term (0-2 years): Development & testing of initial software toolkit using inhouse storage and computer cluster
- Mid-Term (2-5 years): Initial transfer, testing & evaluation of toolkit to IHTM data repository;
- Long-Term (5-10 years): Transfer of toolkit to other disciplines and stakeholders

Contact Information:
Danny Marks, Danny.Marks@usda.gov
Fred Pierson, RL Fred.Pierson@usda.gov
USDA-ARS, Northwest Watershed Research Center

CHALLENGE: Incorporate Channel Transmission Losses into the WRF Hydrologic Model to Improve Estimate of Recharge, Water Availability, and flood peaks in Arid & Semiarid Environments

Challenge: In the hot deserts valleys of much of the western US there is strong evidence that little or not deep groundwater recharge occurs in the upland (inter-channel) portions of a watershed (Walvoord et al. 2002). Only where runoff water is concentrated in areas of high infiltration rates such as ephemeral channels (common in the Western US) will it recharge groundwater.

Context: The Western U.S. is dominated by non-perennial (ephemeral or intermittent) where Trans. Losses and ephemeral channel recharge can be large (Goodrich et al. 2004)

If IHTM capability existed, how would it enhance our ability to address the problem(s)?

More accurately estimate transmission losses & provide an upper bound on channel recharge and improved estimates of peak runoff rate and are thus also important for flood prediction.

If IHTM capability existed, how would it impact and benefit:

- Society: Improved Est. of Western water availability & manage runoff to enhance recharge.
- Science: More accurately close the water budget over large areas

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): NOAA, USGS, USACE, Water providers and planners

Potential "Users"/"Operators" of IHTM Capabilities: Bureau of Reclamation, Army Core Eng.

Potential "Developers" of IHTM Capabilities: NOAA, USDA-ARS, U. Arizona

Scientific and Technical Challenges for IHTM Development: Coupled infiltration & routing

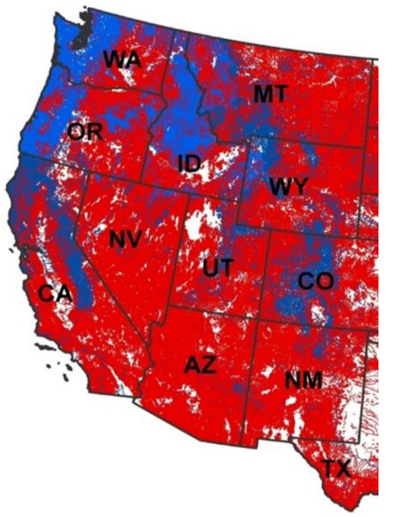
Opportunity for IHTM development based on this specific use-case

- Better representation of Western Watershed Hydrology
- Incorporate ET of Ephemeral stream side vegetation
- Remote characterization of channel bed material and substrate

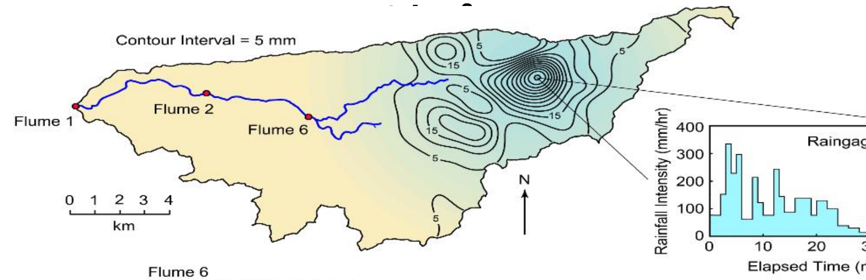
Phased Approach to Development:

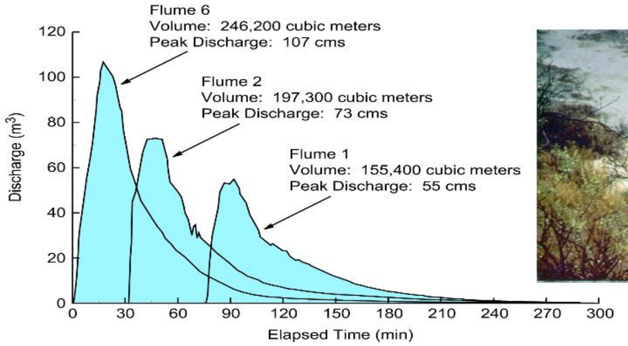
Near-Term (0-2 yrs): Initial testing for WRF complete – Lahmers et al., 2019
Mid-Term (2-5 yrs): Further refinement and broader validation

Non-Perennial	
Arizona	94 %
Nevada	89
New Mexico	88
Utah	79
Colorado	68
California	66
Wyoming	66
Montana	63
Washington	



USDA-ARS Walnut G[illegible]l Watershed





USDA/ARS POC:
David Goodrich, ARS, (520) 603-2194
Dave.goodrich@ars.usda.gov

Aging Dam and Levee Infrastructure and Dam Breach Analysis

Water-related challenge(s):
- Hazard Creep – Change in land use from agriculture to urban creating an increase risk for loss of life if dam failure were to occur.
- Aging infrastructure with structural deterioration and sedimentation of reservoirs reducing flood storage.
- Lack of real-time reservoir and dam/levee data for monitor drought and flood conditions.

Place: Nationwide across urban, suburban, and rural settings.

Primary Stakeholders: USDA-Natural Resources Conservation Service, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Federal Emergency Management Agency, National Weather Service, U.S. Geological Survey, State Dam Safety Offices, National Association of Conservation Districts, Emergency Managers, Floodplain Managers, Insurance Associations, Lending Institutions, Rural Water Districts, and Municipalities.

If IHTM capability existed, how could it be used to better address existing challenges? IHTM capacity would allow integration of current and new monitoring data with historic data. Improve hydrologic and soil parameter inputs for dam and/or levee breach prediction. Lead to development of new technology and beneficial uses dams and reservoirs have to offer. Discovery of new approaches for maintaining a proper balance from our uplands to our rivers' outlet.

Scientific and Technical Challenges for IHTM Development:
- Standardization of instrumentation and higher density sensor network needed in vicinity of reservoirs, dams, and levees.
- Reliable and/or new ground penetrating technology for mapping dams and levees.

IHTM Impact Scientific:
- Improves coordination and sharing of data.
- Expands the access to large data sets for a wider range of computational model utilization.
- Identifies new avenues for research for improving the design and analysis of safe, economical structures and channels for the conveyance, storage, disposal, and measurement of runoff waters.

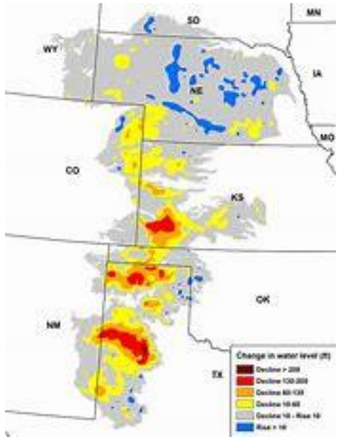
IHTM Impact Societal:
- Allow emergency managers and state dam safety offices to access data for improving emergency action plans.
- Informs policy makers in the development of zoning regulations and insurance policies.
- Allows lending institutions to make better risk informed decisions in residential and businesses impacted by flooding.
- Safeguard food, water, infrastructure, and natural resources through flood protection.

Key Milestones:
- Near-Term (0-2 years): Identify data sources, integrate current and historic data, and identify and agree to standardization of instrumentation for monitoring system.
- Mid-Term (2-5 years): Set-up pilot program for monitoring reservoir and dam/levee network and begin development of data sharing platform.
- Long-Term (5-10 years): Expand reservoir and dam levee monitoring network and begin development of public interface for emergency managers, state dam safety officials, etc.

Contact Information:

Sherry Hunt, (405) 624-4135 ext. 222; Sherry.Hunt@usda.gov
USDA-ARS, Hydraulic Engineering Research Unit, Stillwater, OK

Land Stewardship Use Case: A solution to “go-back” land—restoring abandoned farmland and sustaining rural communities



Water-related challenge(s):

- The Ogallala Aquifer is over-appropriated, with irrigated agriculture as the largest water consumer (94%). NASA’s GRACE mission showed the Ogallala is pumped at 10 times the rate of replenishment.
- Without proactively altering the irrigated agriculture supported by groundwater from the southern Ogallala Aquifer, by 2040, producers will be forced to abandon farms without viable rainfed production.
- High Plains farmland is valued and insured by its ability to be irrigated. Abandoned farmland without intervention reverts to “go-back” land conditions--dominated by invasive weeds, poor soil holding capacity that leads to Dust Bowl-like environments

Context: Supporting 20% of total U.S. production of wheat, corn, cotton, and cattle, the Ogallala Aquifer system is key to U.S. food production today and into the future. Highly productive land could be abandoned in four states (Kansas, Oklahoma, Texas and Colorado), potentially losing $2.2 billion per year.

If IHTM capability existed? Help assess agroecosystem and human adaptation to groundwater; identify groundwater availability to ensure soil retention, grazeable plants established and sustained, and novel agricultural enterprises that maintain viability of traditional rural economics impacted by climate change.

If IHTM capability existed, how would it impact and benefit:

- *Scientific:* Coupled models that integrate depletion rates with managed aquifer recharge (MAR); model plant community dynamics to establish the proxy ag enterprise and ensure enterprise sustainability.
- *Societal: A*dapt agriculture and rural infrastructure to the impending lack of water. Actions need to be driven at the local and state levels, with IHTM providing a supportive, coordinating and facilitation role.

Potential Stakeholders: State geological surveys, water agencies and centers, private and academic subject-matter and extension experts (biophysical and socioeconomic), local and regional irrigation companies and districts, producers and their supporting communities.

Potential “Developers”: University experts funded by NSF, USDA NIFA, ARS, USDOE; others at USDA NRCS, ERS, USFS Climate Hubs, USEPA, NASA, USDOI-BuRec, USGS, USACE

Scientific and Technical Challenges for IHTM Development: Detailed representation of both surface water and groundwater processes, and ecosystem interactions must be included. Model coupling for large-scale mixed agro-rural aquifers, optimization and validation, code linkages between groundwater and irrigation, stress partitioning, scalability to larger than small regions or watersheds through array allocation,

Opportunity for IHTM development based on this specific use-case: Better integration of hydrologic and ecosystem modeling with climate effects; better scalability and automation.

James P. Dobrowolski USDA/NIFA
202-420-8918
james.dobrowolski@usda.gov

Key Milestones:

Near-Term (0-2 yrs): Loose coupling of hydrologic model with cellular automata based multi-criteria decision analysis framework;

Mid-Term (2-5 yrs): Tightly coupled groundwater + irrigation + land use change model;

Long-Term (5-10 yrs): Working coupled model accounting for rate of groundwater depletion, ‘restoration” of novel sustainable plant assemblage that supports local communities.

EXAMPLE: Hydro-Economic Resilience & Western Water Stress (FEWSION)

Water-related challenge(s): Water scarcity, drought, and long term socio-economic adaptation (especially for Western FEW and agriculture)

Context: Long term adaptation to water scarcity in the western U.S. poses a major challenge for policy and economics. The hydrology is simple: less renewably available water, more demand for water and water-intensive goods like food and energy, and dwindling groundwater stocks. The policy issues are vast and complex, and national in scope, and touch every aspect of U.S. society, along with nearly every mission agency. We were good at growing; do we know how to adapt and selectively shrink our hydro-economy? Do we understand the systemic affects of our policies? How can we design systemically resilient policies?

If IHTM capability existed, how would it enhance our ability to address the problem(s)? Accurate modeling of long term socio-economic, ecological, and hydrological consequences of current policies and technologies enable development of better policy, to preserve and protect vulnerable and irresilient communities- or assist with their reinvention and transition away from water uses.

If IHTM capability existed, how would it impact and benefit:

Society: Avoiding the deepest pain of water stress: FEW insecurity, decimation of rural western communities, ecological devastation

Science: SETS framework for studying complex coupled human natural systems; social science of policy and adaptation

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): Everyone, most mission agencies

Scientific and Technical Challenges for IHTM Development: Especially (1) data, and (2) is it impossible to model these complex systems?

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities: Data aggregation and modeling of multi-agency data resources (FEWSION)

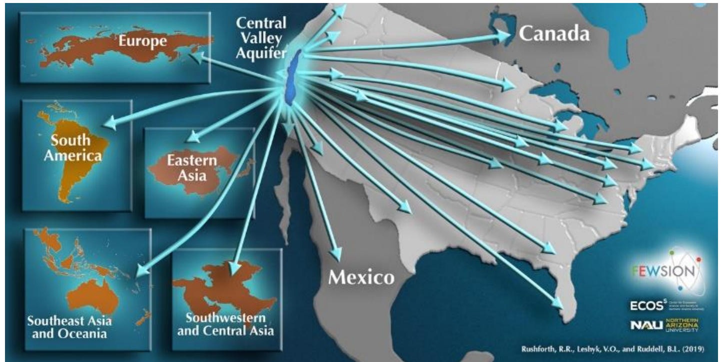
Development of new capabilities: Multiscale FEW and systems modeling including decision making and policy dimensions

Key Milestones and Phased Development:

Near-Term (0-2 yrs): FEWSION data products and descriptive science, versions 1-3

Mid-Term (2-5 yrs): Integration of FEWSION data products into mission agency decision and response, exploration of model potential

Long-Term (5-10 yrs): Partnerships with many agencies, labs, academics to build and understand long term FEWS models



Benjamin L. Ruddell, Director SICCS, Northern Arizona University, Benjamin.Ruddell@nau.edu

Water Sustainability for Managed Watershed Systems: Columbia River Basin Use Case

Water-related challenge(s):

- Projected climate change in pacific northwest, warmer and wetter winters with less snow and more rain, warmer and drier summers, will profoundly change future water availability.
- Human activities significantly alter the water quantity and quality: dam operations, irrigation, groundwater pumping, etc

Context: Columbia River is the 4th-largest river in the US, draining portions of 5 U.S. states and 2 Canadian provinces. It has 14 hydroelectric dams on its main stem and many more in its tributaries. It is an important resource for agriculture, recreation, and fisheries. Environmental flow concept has been introduced to adaptive river management to protect salmonid species.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? IHTM capacity would allow for science informed water resources management under changing climate, especially under extreme conditions, such as flood and drought. Long-term climate predictions could be used to form mitigation strategy and enhance sustainability.

If IHTM capability existed, how would it impact and benefit:

Society: enhance resilience to extreme events

Science: coupled hydrobiogeochemical models with heat transport across all compartments of the watersheds. Water management impacts explicitly represented.

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): Army Corp of Engineers, NOAA, BPA, Tribes, DOE, BoR, USGS, EPA, farmers

Potential "Users"/"Operators" of IHTM Capabilities: Army Corp of Engineers, NOAA,USGS, EPA, DOE, BPA

Potential "Developers" of IHTM Capabilities: DOE, NCAR, USGS, NOAA

Scientific and Technical Challenges for IHTM Development: interoperabilility, parallelization, scaling, integration with monitoring data

Key Milestones and Phased Development:

Near-Term (0-2 yrs): incorporate river corridor processes into watershed biogeochemistry

Mid-Term (2-5 yrs): data assimilation system to interact model with monitoring data

Long-Term (5-10 yrs): couple with WRF for distributed forcing to watershed systems

Contributors: Xingyuan Chen and Tim Scheibe (PNNL), David Moulton (LANL), Glenn Hammond (Sandia), Jesus Gomez-Velez (Vanderbilt Univ)

Meeting Future Water Needs to Accommodate Western Population Growth

Water-related challenge(s):
- Water managers need medium and long-term predictions at the basin level to better plan for water use
- In snow-dominated systems, snow depth and snow water equivalent are measured by the SNOTEL network and snow surveys, but snow depth and snow water equivalent can change significantly by elevation over short horizontal distances
- Snow depth is highly influenced by a small number major storms (atmospheric rivers) that have proven difficult to predict
- Western states are facing excess nutrient-related impacts to lakes and other waters that will likely increase due to expanded population

Context: Several western cities expect significant population growth over the next decade. With limited water availability already being an issue and emerging water pollution issues, western water managers are faced with many management challenges. These include managing the timing/quantity of inter-basin water transfers, operating on limited information on medium and long-term water runoff, while at the same time mitigating water quality impacts of a more urbanized environment and maintaining instream flow.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? IHTM could provide better integration of remote sensing data and SNOTEL data (similar to what's been done in CA) to give a better understanding of water storage via snow. This coupled with better seasonal temperature and rain predictions will help water managers better plan for the timing of the runoff. More integrated models will also allow for a better understanding of pollutant flows through the water networks to ensure that water quality is fit for the use.

If IHTM capability existed, how would it impact and benefit:

Society: Less uncertainty in water management in the west, buffer against drought, prioritize infrastructure investment

Science: Improved prediction capability for both precipitation and major weather events, identify streams for restoration to improve water quantity/quality

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): State water resource and water quality agencies, conservation districts, and water providers.
Potential "Users"/"Operators" of IHTM Capabilities: NRCS, NOAA, state water resource agencies
Potential "Developers" of IHTM Capabilities: NRCS, NASA, NOAA, USGS, Academia, States, DOE, and EPA

Scientific and Technical Challenges for IHTM Development:
- Medium and long-term forecasts are unreliable for basin predictions
- Major 'single-event' storms are difficult to predict
- Connecting the water quantity and water quality communities

Dwane Young, U.S. EPA Office of Water, 202-566-1214

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities: SNOTEL with Remote Sensing and water quantity with water quality modeling and prediction

Development of new capabilities: medium and long-term predictions; better correlations between remote sensed data and snowpack

Key Milestones and Phased Development:

Near-Term (0-2 yrs): Expanded remote sensing for snow-depth coupled with SNOTEL and snow surveys

Mid-Term (2-5 yrs): Coupled models including the modeling of nutrient transport through western basins and lakes

Long-Term (5-10 yrs): Integrated modeling framework with seasonal prediction capabilities, timing of flow and estimated pollutant loadings through the withdrawal and discharge processes.

Groundwater depletion as a coupled human and natural system

Water-related challenge(s): Groundwater resources in many agricultural region in the western US are being depleted as a result of irrigation.

Context: Irrigation demand indirectly couples deep groundwater to surface water, surface ecosystems, and the climate. All of these couplings are directly impacted by human activities through land use patterns, agricultural practices, and population dynamics. Future water security can thus only be understood as an integrated system. Coupling of hyper-resolution surface/subsurface hydrology models, land surface processes, deep groundwater models, and models for human systems would improve system understanding.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? Better representation of human-mediated coupling between climate and groundwater systems would improve ability to evaluate long-term management strategies.

If IHTM capability existed, how would it impact and benefit:

Society: Better long-term projections of groundwater depletion. Support design of management practices.

Science: Better understanding of how agricultural economics and regulatory practice impacts depletion in a changing climate.

Potential Stakeholders: Water managers. State aquifer regulators.
Potential Users: USGS WSCs, state and local aquifer authorities. **Potential Developers:** USGS WMA, USGS WSCs, DOE

Scientific and Technical Challenges for IHTM Development: Computationally demanding simulations. Economic/social models for irrigation demand and land use change. Managing complexity in coupled models. Data assimilation and model evaluation.

Opportunity for IHTM development based on this specific use-case: Interface design to support model coupling. Adaptation of integrated surface/subsurface hydrology codes to heterogeneous computer architectures. Agent-based models for human system components.

Key Milestones and Phased Development:
Near-Term (0-2 yrs): Couple existing groundwater models to integrated surface/subsurface models.
Mid-Term (2-5 yrs): Hyper-resolution (100 m) surface/subsurface hydrology model of California Central Valley on leadership-class computers.
Long-Term (5-10 yrs): Models for human system components (economic/social). Fully coupled model.

Scott Painter and Ethan Coon, Oak Ridge National Laboratory paintersl@ornl.gov

Integration of Coastal and Hydrologic Models

Scenario/Place: US Gulf and Atlantic Coasts
Problem: Hurricanes bring heavy inland rainfall and coastal surges that impact watershed drainage. Models are not fully integrated.
Potential Stakeholders: State and local agencies, and first responders
IHTM Role: Integration of coastal and hydrologic models allows for identification of optimal solutions for flood management and flood risk reduction.
Potential IHTM Customers: National Hurricane Center, USACE Water Managers, FEMA, DHS, State and local agencies, and first responders
IHTM Impacts:

- *Scientific:* Coupled models that integrate storm surge and watershed runoff to optimize the system for coordinated objectives.
- *Societal:* Reduced flooding impact through better planning, design and emergency management.
- *USACE Mission:* Improved flood risk management (inland and coastal)

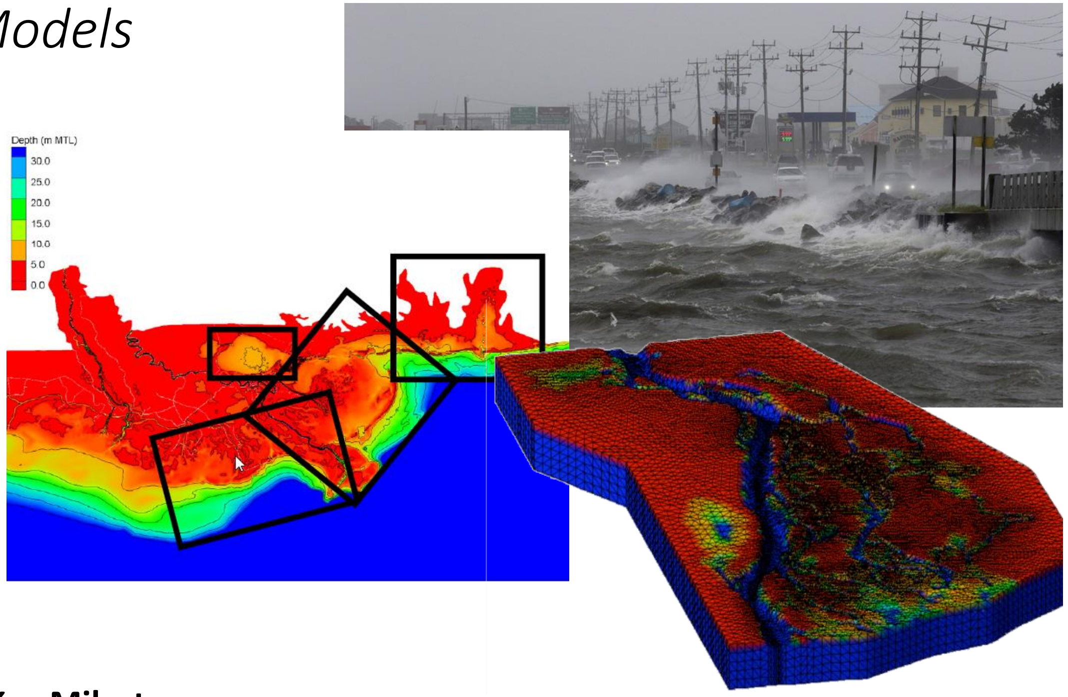
IHTM Needs:

- Accurately represent combined effects from storm surge & rainfall/runoff
- Provide timely information for emergency response
- Make information comprehensible and accessible

Technical Barriers:

- Parallelization and optimization of coupled codes
- Standardized I/O
- Model coupling and validation
- Access and linking to forcing and assimilation data

Potential IHTM "Developers": USACE (ERDC, IWR-HEC), NOAA National Water Center, USGS, Oak Ridge National Laboratory, NASA



Key Milestones:

Near-Term (0-2 yrs): Off-line, loose coupling of surge & runoff models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational coastal hazards system that accounts for both surge and runoff

USACE POC(s):

- Mark Wahl, 937.255.8309, Mark.D.Wahl@usace.army.mil
- Mike Follum, 601.634.2639, michael.l.Follum@usace.army.mil
- Chris Massey, 601.634.2406, chris.massey@erdc.dren.mil

Urban Flooding

Scenario/Place: Urban and suburban areas nationwide
Problem: Urban flooding, non-stationary drivers: both land use and climate

Potential Stakeholders: Communities, States, Water & Sewer Utilities, Watershed Associations
IHTM Role: Integration of hydrologic models, long-term precipitation records, and climate models to improve forecasting and uncertainty quantification around flood and flood frequency predictions.
Potential IHTM Customers: DOI, USACE, FEMA, FHWA, NWS, EPA, State and local DOTs

If IHTM capability existed, how could it be used to better address the problem?

- Current design approaches use historical precipitation frequency with, at best, some extra factor of safety applied. New capability would result in possibly more economical designs with understood risk profile.

IHTM Impacts:

- *Scientific:* New approaches for drainage infrastructure design addressing both sizing and uncertainty concerns.
- *Societal:* Increased safety and reduced infrastructure service down time.

IHTM Needs:

- Hydrologic community agreement on approach and climate scenarios considered
- High quality geospatial data: land use (and forecasted land use), precipitation frequency
- Effective visualization tools and products

Technical Barriers:

- Geospatial, frequency analyzed climate model output does not yet exist
- Projected future land use is highly uncertain and not uniformly available, even at state levels
- Many scenarios can be explored – identification of focus scenarios requires consensus
- Large uncertainty bounds could render results un-actionable

Potential IHTM "Developers": USDA/ARS, USGS, NWS

Localized flooding on Canal Road in Washington DC due to ~1000-year, 1-hour rainfall event in July 2019.

Key Milestones:

- Near-Term (0-2 yrs): Agreement on method and scenarios
- Mid-Term (2-5 yrs): "Production mode" and uncertainty quantification
- Long-Term (5-10 yrs): Dissemination and refinement

USDA/ARS POC:

Glenn Moglen, ARS, (301) 504-8745
glenn.moglen@ars.usda.gov

Flooding During Extreme Events

Water-related Challenge(s):

- Flooding during extreme events arises from a complex set of interrelated factors
- During a wintertime Nor'easter, for example, flooding is influenced by ocean storm surge, river ice jams, rain-on-snow melt, frozen ground, reservoir regulation, groundwater and urban factors.
- Flooding can impact water quality, causing sewer system overflow and agricultural runoff
- A national integrated model is needed to tie relevant processes together to accurately represent the timing, location and magnitude of flooding so as to enable effective decision support and response activities

Context: Current operational hydrologic models only capture a subset of the processes that impact flooding, leaving a significant portion of the United States without an accurate integrated forecast. For example, over 120 million people live along the coastline where the combined impacts of coastal and freshwater flooding are not represented. Lack of coupling to water quality, groundwater and urban models exacerbates the issue.

If an IHTM capability existed, how could it be used to better address the problem(s)?
An IHTM capacity would link processes together to produce an accurate forecast of floodwaters and their impacts. This would aid forecasters and emergency responders, and ultimately benefit the public who rely on such forecasts for safety and protection of property.

Potential Stakeholders: Forecasters and Emergency Responders
Potential "Users" of IHTM Capabilities: NWS Field Offices, FEMA, State and Local Emergency Response
Potential "Developers" of IHTM Capabilities: NOAA, USGS, DOE, ACE, EPA, NCAR, NASA, Academia

NOAA NWS OWP
Contact: Brian Cosgrove
brian.cosgrove@noaa.gov

Scientific and Technical Challenges for IHTM Development: Access to sufficient operational compute and storage. Effective visualization and dissemination of vast quantities of data. Optimization and linkage of disparate sets of operational process models. Access to required forcing and observational data.

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate reservoir operation, coastal coupling, cold land processes, groundwater, water-quality, hyper-resolution urban impacts.
- *Societal:* Improved flood disaster response and mitigation, reducing loss of life and damage to property and commerce.

Key Milestones:
Near-Term (0-2 yrs): Limited domain coupling of freshwater and estuary models. Inclusion of limited anthropogenics.
Mid-Term (2-5 yrs): Full operational coupling of freshwater and estuary models. Testing of cold process, urban, groundwater and water quality components. Improved anthropogenics.
Long-Term (5-10 yrs): Full-featured operational system

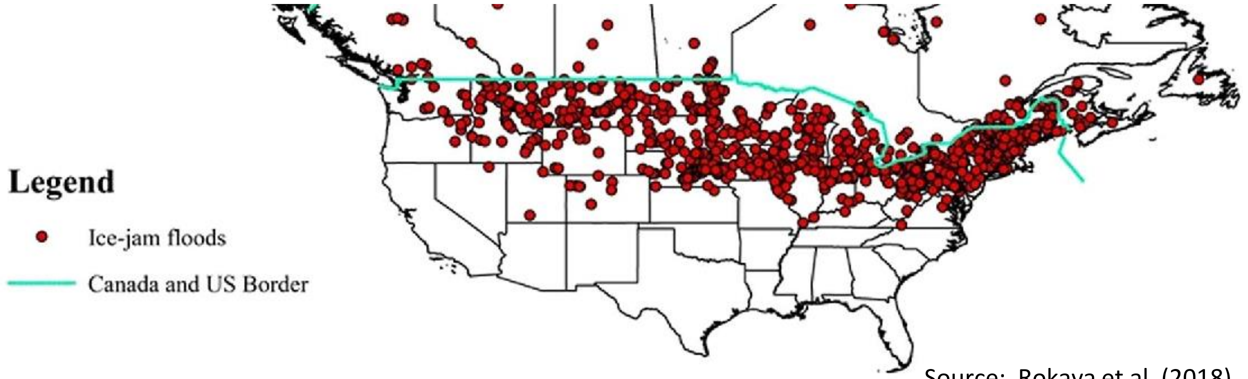
Springtime Ice Jam Flooding in the Northeast

Water-related challenge(s): Spring flood risks can difficult to estimate, particularly in light of groundwater priming and conditions that can arise from mixed constituents in surface flows (i.e. ice and water). With increased meteorological variability in this region, increased wintertime precipitation and rapid melt have the potential to trigger severe flooding episodes.

Context: In the springtime, warm temperatures and rainfall in the Northeast can rapidly lead to flooding due to the formation of ice jams. The most devastating winter floods within New England have been associated with ice jams. Infrastructure near rivers and streams are most susceptible to flooding from ice jams.

If IHTM capability existed, how would it enhance our ability to address the problem(s)?
The capability would allow us to examine the surface and subsurface conditions that give rise to ice jam flooding and assess flood risk in light of pending meteorology. In particular, IHTM that supports the modeling of ice transport by surface flows would be necessary.

If IHTM capability existed, how would it impact and benefit:
Society: improve risk assessment of flooding conditions along streams and rivers due to ice jamming.
Science: understand the conditions that naturally give rise to ice jamming and project risk of ice jam flooding under changing climatological conditions. Develop strategies for mitigating damage from flooding.



Source: Rokaya et al. (2018)

Potential Stakeholders : DOE, USGS, water managers, states, insurance
Potential “Users”/”Operators” of IHTM Capabilities: DOE, FEMA, USACE, USGS, water managers, states, insurance
Potential “Developers” of IHTM Capabilities: DOE, USGS, NOAA, NSF

Scientific and Technical Challenges for IHTM Development:
- Difficult to model the fine-scale processes that give rise to river ice
- This is a problem with a significant multi-scale nature

Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: <need to harmonize capabilities with other agencies>
Development of new capabilities: <harmonize assumptions, develop datasets, new couplings>

Phased Approach to Development:
Near-Term (0-2 yrs):
Mid-Term (2-5 yrs):
Long-Term (5-10 yrs):

Department of Energy,
Multi-Sector Dynamics program area
Contact: Bob Vallario
(Bob.Vallario@science.doe.gov)

Forecasting Impacts of Disturbance Events in the Rocky Mountain West

Water-related Challenge(s):

- Wildfire and other disturbance events that remove forest cover increase risks of flooding, soil erosion, river and reservoir sedimentation, and debris-flow generation.
- Sediment delivery to stream channels impairs water quality, and can lead to increased flood risk (where sedimentation raises channel elevation) and reduced reservoir lifespan.
- Increasing wildfire occurrence and severity, coupled with growing population, raises risk.

Burned slope, Colorado Front Range (Rengers et al., 2016)

Context: Hazards posed by wildfire, flooding, landsliding, erosion, and sedimentation are not independent, but form part of a connected cascade. In mountainous regions like much of the western United States, the most costly impacts of floods often involve sediment: both as a pollutant, as in the form of damage to infrastructure through erosion and sedimentation.

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for an integrated analysis and modeling of past (for improved understanding) and potential future (for forecasting) disturbance events. For example, an integrated modeling framework could address questions such as: if a wildfire of a given size occurred in the mountains west of Denver, Colorado, what would be the nature and magnitude of flood and sediment risk, and how could that risk best be mitigated?

Potential Stakeholders: Colorado Front Range cities and counties
Potential "Users" of IHTM Capabilities: USGS landslide hazards group, USGS water science, NOAA
Potential "Developers" of IHTM Capabilities: CSDMS, CIRES, USGS water science, NCAR

Contact:
Greg Tucker (gtucker@colorado.edu)
University of Colorado, Boulder

Scientific and Technical Challenges for IHTM Development: providing model and data components with Basic Model Interface (BMI); wrapping as Python Modeling Tool (pymt) components; modifying/developing components; coupling; testing against case-study datasets

Impact of IHTM capability to

- *Scientific:* Better mechanistic understanding of the "disturbance cascade" and the processes that contribute to it.
- *Societal:* Improved management of disturbance-related flooding, landslide, and sedimentation risks.

Key Milestones:
Near-Term (0-2 yrs): model identification, adaptation, & wrapping
Mid-Term (2-5 yrs): develop framework; test against data
Long-Term (5-10 yrs): system for scenario-based assessment

Flooding for Mid-Atlantic Coastal Localities

Flooding-related Challenge(s):

- Surface flooding in costal localities is driven by both storm surge and intense precipitation events
- Run-off from land areas is affected by antecedent weather events, landuse practices, topography, and stormwater management practices
- The problem is frequently very localized and future sea level rise and land development patterns will likely increase this risk.

Context: Much of the mid-Atlantic coastal plain has low relief, very variable landuse, significant exposure to both tropical and extra-tropical weather events, and lots of rivers and streams that have very responsive hydrographs. Forecasting flooding events both in long-term and short-term scenarios is difficult because of the need to integrate storm surge and runoff effectively.

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for an integrated assessment of water inputs to coastal areas, enhancing risk assessments for both short-term and long-term planning.

Potential Stakeholders: Coastal localities in Maryland, Virginia, and North Carolina, the Chesapeake Bay Program and the Albemarle Pamlico National Estuary Partnership
Potential "Users" of IHTM Capabilities: FEMA, EPA, USGS, MEMA, VDEM, NC DPS, MDNR, VDEQ, NCDNR, CBP, APNEP
Potential "Developers" of IHTM Capabilities: USGS, NRCS, DOE, DOE, NOAA, CBP, universities

Scientific and Technical Challenges for IHTM Development: Parallelization and optimization of coupled codes, Standardized I/O, Model coupling and validation, Access and linking to forcing and assimilation data

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate weather and climate drivers over both land and coastal ocean areas for predicting coastal flood risks
- *Societal:* Reduced flood risk exposure, enhanced water quality and water supply management

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that incorporates climate change

Carl Hershner, VIMS, carl@vims.edu

EXAMPLE: Precise Near-Realtime Urban Flood Detection and Prediction (FloodAware)

Water-related challenge(s): Urban Flooding; realtime detection, communication, data assimilation, warnings, prediction, assessment

Context: Human-scale, infrastructure-scale, near-realtime monitoring and prediction of flooding in cities is a high value frontier for integrated federal and academic engineering and science. The vast majority of infrastructure investment, and economic impact, relating to floods centers on cities; yet we lack a national (or even local) monitoring or prediction capability to enable infrastructure operation, adaptation to climate change, assessment of infrastructure efficacy, public safety warnings, or smart city operations. Emerging solutions exist.

If IHTM capability existed, how would it enhance our ability to address the problem(s)? Precise near-realtime detection or prediction of urban flooding fills the basic information gap at this scale, enabling many applications and studies.

If IHTM capability existed, how would it impact and benefit:

Society: Public safety, stormwater infrastructure adaptation and improvement, property protection, involving several mission agencies

Science: SETS framework studies for hydrology and flooding in cities, Smart Cities research, Urban Hydrology

Potential Stakeholders (e.g. specific entities that would benefit from IHTM Capabilities): NWS, DHS, USGS, DoD, DoT, State & Local

Scientific and Technical Challenges for IHTM Development: Socio-technical, image processing, sensor networks, citizen science, data quality control, data assimilation

Opportunity for IHTM development based on this specific use-case

Better integration of existing capabilities: NWS warning and modeling and communications, traffic camera and monitoring, public safety

Development of new capabilities: Near-realtime detection and measurement of inundation, AI/image-processing, social network, Apps

Key Milestones and Phased Development:

Near-Term (0-2 yrs): Piloting camera-based and citizen science measurement of inundation in urban areas (FloodAware, etc.)

Mid-Term (2-5 yrs): Trial deployment of capabilities by NWS, ?, integrated with existing modeling (NWM?) and warning systems

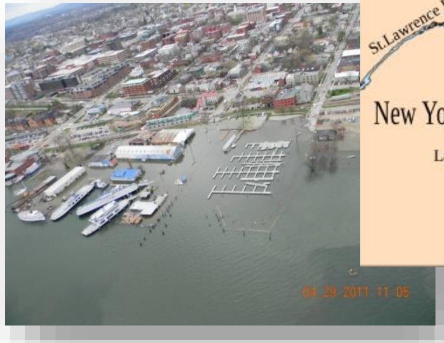
Long-Term (5-10 yrs): Maturing national networks capable of precise detection in all US cities. Data assimilation to improve prediction.

Benjamin L. Ruddell, Director SICCS,
Northern Arizona University,
Benjamin.Ruddell@nau.edu

Use-Case for Lake Champlain-Richelieu River Flood Forecasting

Water-related Challenge(s):

- In recent years, severe floods resulting from intense spring runoff and rain events caused significant destruction of property and infrastructure in the binational Lake Champlain-Richelieu River Basin.
- Storm surge events and wind waves led to even higher lake water levels and further damage.
- Lake discharge and local inflows to the Richelieu River caused damages downstream of the lake.
- Climate change can impact intensity of precipitation and runoff may increase flood risk in the future.



Photos credit: Lake Champlain Basin Program

Context: Lake Champlain, bordered by Vermont, New York and Quebec, is the 6th largest lakes in the US. Record snow melt and heavy spring rains in 2011 led to record-setting flooding that lasted 67 days. Lake level rose by about 2 m, lake area increased by 15%. Long fetch (~200 km) and shallow average depth (~20 m) exacerbated situation due to large storm surges and wind waves.

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity (e.g. operational flood forecasting system for the Lake Champlain-Richelieu River basin) would help citizens and water resource management agencies better anticipate and prepare for flood events. Water quality modeling could also help address harmful algal bloom issues.

Potential Stakeholders: International Joint Commission, navigation, coastal communities, recreational users
Potential "Users" of IHTM Capabilities: NOAA, ECCC, Province of Quebec, Met. Services of Canada, academic researchers
Potential "Developers" of IHTM Capabilities: NOAA, ECCC, academic researchers

Scientific and Technical Challenges for IHTM Development: Accurate prediction of precipitation and runoff, coupling terrestrial models with lake models, coupling wave and hydrodynamic models. Coordination of forecasts and warnings with the Province of Quebec.

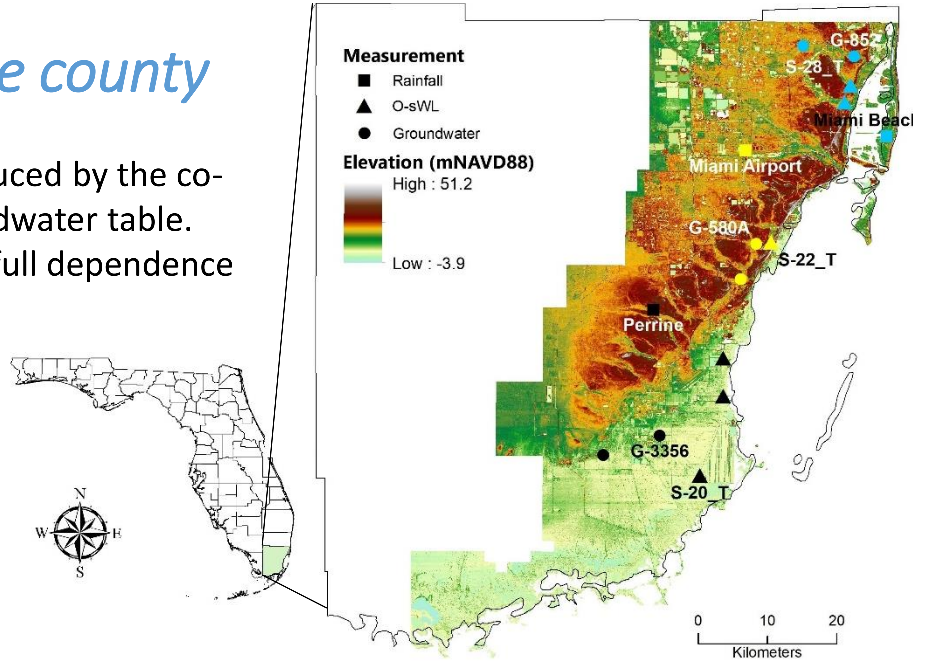
Impact of IHTM capability to

- *Scientific:* Coupled models that integrate terrestrial runoff with lake hydrodynamic and wave models
- *Societal:* Improved flood forecasts for emergency managers and coastal communities

Key Milestones:
Near-Term (0-2 yrs): One-way coupling of land and lake models
Mid-Term (2-5 yrs): Fully coupled land-lake models
Long-Term (5-10 yrs): Modeling system for climate scenario, outflow and terrestrial flow alteration testing for use in water management decisions

Contact:
Deborah Lee (deborah.lee@noaa.gov)
Jesse Feyen (jesse.feyen@noaa.gov)

Compound flooding in Miami-Dade county



Water-related Challenge(s):

- Miami-Dade County is a heavily managed low-lying coastal catchment vulnerable to flooding induced by the co-occurrence of multiple dependent drivers including heavy rainfall, storm surge, and a high groundwater table.
- Structural design assessments presently undertaken by the Water Management District assume full dependence between rainfall and ocean-side still water level (surge + tide), potentially leading to over-design.
- Future sea-level rise and possible changes in storminess will likely further increase flood risk.

Context:

Miami-Dade has more people living on land less than 4 feet above the local high tide line than any US state, except Florida itself and Louisiana. In terms of property damage, Miami is considered the world's most vulnerable city to storm-related flooding and sea-level rise.

If IHTM capability existed, how could it be used to better address the problem(s)?

IHTM capacity would potentially allow for the dependence between the meteorological, oceanographic, and hydrological variables responsible for (compound) flooding to be captured more robustly and at more sites than is presently possible.

Potential Stakeholders: The City of Miami, The Miami River Commission, South Florida Water Management District (SFWMD)
Potential "Users" of IHTM Capabilities: SFWMD and any other agencies charged with managing (compound) flooding risks.
Potential "Developers" of IHTM Capabilities: Universities, federal (USACE, DOE, NOAA) and state (e.g. SFWMD) agencies

Scientific and Technical Challenges for IHTM Development: Modelling framework incorporating the relevant drivers for compound flooding as inputs/outputs, at an appropriate spatial and temporal resolution, and able to capture the processes leading to correlation in the key drivers.

Impact of IHTM capability to

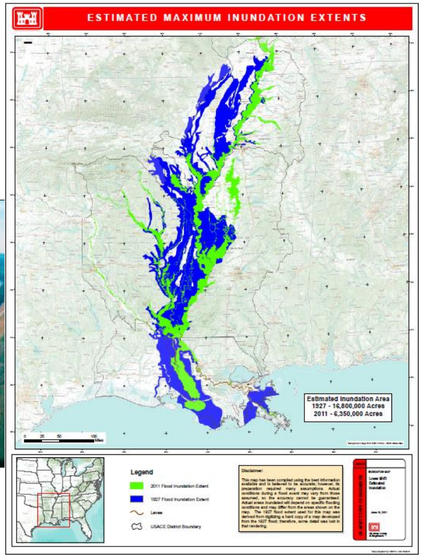
- *Scientific:* Methodology aiding more efficient design of flood defence/ water management structures in locations exposed to compound flooding.
- *Societal:* More robust flood risk management in densely populated regions.

Key Milestones:

Near-Term (Now): develop a robust statistical methodology
Mid-Term (1-2 yrs): couple with hydrological/hydraulic models
Long-Term (5-10 yrs): fully integrate into structural design assessment

Thomas Wahl *Civil, Environmental and Construction Engineering Department & National Center for Integrated Coastal Research. University of Central Florida.*
t.wahl@ucf.edu

Use-Case for Lower Ohio-Mississippi River Flood Control



Water-related Challenge(s):

- The Mississippi River drains 40% of the CONUS and is the third largest river in the world.
- Flooding and nutrient transport affects people and the environment along the river and the Gulf of Mexico.
- Increasing precipitation and runoff due to a changing climate will exacerbate both flooding and nutrient loading.

Context: The Mississippi River and Tributaries Project, along with reservoir systems constructed on the Missouri, Ohio, Tennessee and Cumberland Rivers constitute the largest flood risk reduction system on the planet. The system reduces flooding risk preventing billions of dollars of damages and protecting more than 1.5 million acres along the lower Mississippi River (below Cairo, IL).

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for common operating picture amongst the management agencies (NOAA, USACE, TVA, Mississippi River Commission) and emergency responders (FEMA, States) and provide an integrated assessment of water availability for ecosystem and human needs under normal and drought conditions.

Potential Stakeholders: Mississippi River Commission, commercial navigation, Mississippi Valley agriculture, City of New Orleans, Illinois, Indiana, Ohio, Kentucky, Tennessee, Missouri, Arkansas, Mississippi, Louisiana
Potential "Users" of IHTM Capabilities: NOAA, USACE, USGS, TVA, Mississippi River Commission, State management agencies
Potential "Developers" of IHTM Capabilities: NOAA, USACE, USGS, TVA

Scientific and Technical Challenges for IHTM Development: Incorporating reservoir and navigation structure operations, levee breaches, floodway and backwater operations; obtaining precipitation forecasts with sufficient lead times to make reservoir operation decisions.

Contact: Deborah Lee
(deborah.lee@noaa.gov)

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate reservoir, floodway, and backwater operations, Gulf of Mexico nutrient loading prediction.
- *Societal:* Reduced flooding risk and drought risk to central US.

Key Milestones:
Near-Term (0-2 yrs): Obtain agency buy-in on common models
Mid-Term (2-5 yrs): Integrate reservoir operations
Long-Term (5-10 yrs): Experimental operational system

IHTM: *Frozen ground affected flooding in glacial landscapes.*

David Blodgett, USGS: dblodgett@usgs.gov

Image link.

Water-related challenge(s): Frozen and thawing shallow groundwater, drifted snow, river ice, and other factors of spring melt in the northern tier of the US present major challenges for spring flood prediction. Water quality aspects of this problem are especially difficult.

Context: Field to catchment scale rain-driven spring flooding in frozen agricultural landscapes are complicated requiring integrated models. Soils, shallow groundwater, state of thaw, intensity of rain, tillage practices, manure application, drifted snow, frozen culverts, etc. The image included is a rain on frozen ground and snow event with manure applied over top of the snow. Culverts were clogged due to drifted snow which closed numerous local roads and the manure and other water quality factors had significant impacts on receiving waters.

If IHTM capability existed, how would it enhance our ability to address the problem(s)?
A common system of systems to bring together required data and "mash up" or even tightly couple various predicted components would allow some prediction of the water quality and quantity impacts of such an event.

If IHTM capability existed, how would it impact and benefit:

Society: Predictive capacity (good information) would lead to better short and long term decisions.

Science: Frozen soils and spring melt are poorly modeled in flat terrain.

Potential Stakeholders: Local DOTs, land management decision makers, emergency responders.
Potential "Users"/"Operators" of IHTM Capabilities: USGS WSCs, NWS RFCs, local partners.
Potential "Developers" of IHTM Capabilities: USGS-WMA, NWS-OWP, USDA-ARS, and partners.

Scientific and Technical Challenges for IHTM Development: Real time soils and frozen ground data and predictions, transportation and local water infrastructure state, crop status, manure and fertilizer application, solar impacts of land treatments on snow state, etc.

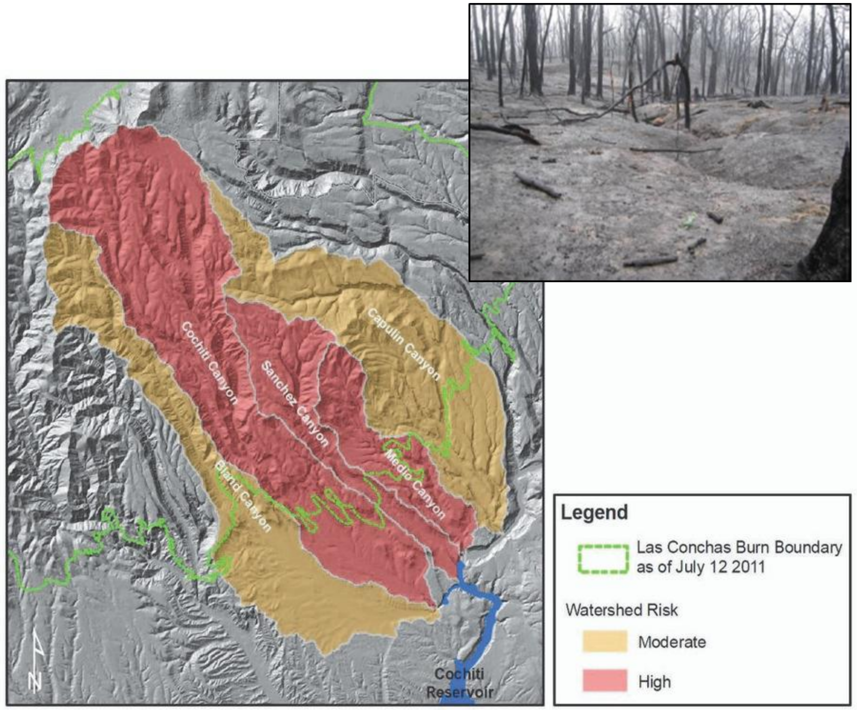
Opportunity for IHTM development based on this specific use-case
Better integration of existing capabilities: Integrate data toward better predictions.
Development of new capabilities: Frozen ground models and real time land cover / use predictions

Key Milestones:
Near-Term (0-2 yrs): Data collaborative
Mid-Term (2-5 yrs): Data-driven model development
Long-Term (5-10 yrs): Decision relevant information

POST-WILDFIRE IMPACTS TO FLOOD RISK MANAGEMENT (FRM): LAS CONCHAS WILDFIRE-NEW MEXICO

Water-related challenge(s): The amount and intensity of large wildfires in the U.S. have become a major concern, especially in the arid and semi-arid western U.S. where over the past decade every state has experienced an increase in the number of large fires according to the National Interagency Fire Center. Post-wildfire regions can experience a spectrum of hydrologic responses ranging from no response to catastrophic floods, deadly debris flows, and destructive sedimentation and has been documented in locations around the U.S. and world.

Context: During the summer of 2011, the Las Conchas Fire burned approximately 634 km in New Mexico. Watersheds inside the Las Conchas Fire limits area are now at significant risk of damage from post-wildfire sedimentation hazards, flooding, mudflows, debris flooding.



If IHTM capability existed, how would it enhance our ability to address the problem(s)?
An integrated approach to modeling is needed to understand the complex interactions between weather, hydrology, hydraulics, soil physics, and plant succession to make decisions about restoration efforts.

Potential Stakeholders: IWR-HEC, USACE-SPA, USACE-SPL, USACE-SPK, USACE-NWP, USACE-NWW, USACE Silver Jackets, Desert Research Institute, USGS, USFS, USDA, and Santa Barbara County.
Potential "Users"/"Operators" of IHTM Capabilities: IWR-HEC, USACE-SPA, USACE-SPL, USACE-SPK, USACE-NWP, USACE Silver Jackets
Potential "Developers" of IHTM Capabilities: USACE ERDC, IWR-HEC, Desert Research Institute, USGS, USFS, and USDA.

Scientific and Technical Challenges for IHTM Development: Limited knowledge of basic processes; coupling diverse model types, i.e. weather, soils, hydrology, hydraulics, plants

Key Milestones and Phased Development:

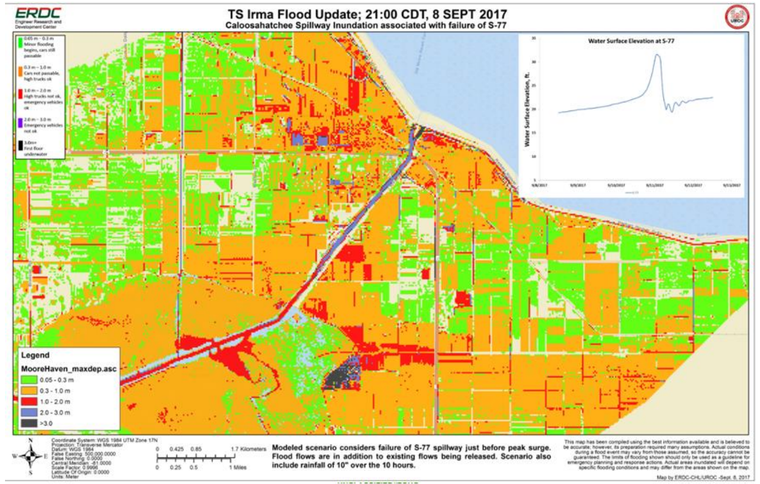
Near-Term (0-2 yrs): Development on fundamental understanding
Mid-Term (2-5 yrs): Development of individual models
Long-Term (5-10 yrs): Integration of individual models

USACE POCs:
- Charles W. Downer, 601.488.9925, Charles.W.Downer@usace.army.mil
- Ian Floyd, 601.634.4160, Ian.E.Floyd@erdc.dren.mil

EXAMPLE: Hurricane Irma, Florida, 2018

Water-related Challenge(s):

- In a changing world of weather, land use, and hydrologic response, current information and capability to simulate and forecast extreme flood risk in complex systems is inadequate.
- Complex flooding events can occur from a variety of sources, rainfall, runoff, storm surge, high river stages, levee overtopping/failure, unanticipated reservoir releases, etc.
- Current flood zone and flood forecast do not include all these complex features and feedbacks leading to an incomplete understanding of the problem and potential effects.



Context: Tropical system Irma threatened almost every part of Florida at one point or another. ERDC provided guidance on a variety of unusual possible scenarios as conditions evolved, including the possible overtopping of the Lake Okeechobee Herbert Hoover dike. The watershed model, GSSHA, was used to simulate potential flooding from these scenarios, such as the flooding near Moore Haven, FL.

If IHTM capability existed, how could it be used to better address the problem(s)?
IHTM capacity would allow for an integrated assessment of complex flood events and provide useful, maybe critical, information about what may occur, including potentially identifying unanticipated flooding hazards due to interactions between multiple flooding mechanisms.

Potential Stakeholders: USACE, FEMA, USGS, NOAA
Potential "Users" of IHTM Capabilities: USACE, FEMA, USGS, NOAA, state flood plain managers, state and city emergency response managers
Potential "Developers" of IHTM Capabilities: USACE ERDC, NOAA/NWC, USGS, NASA

Scientific and Technical Challenges for IHTM Development: The variety and extent of future complex extreme flood events is somewhat overwhelming. A wide variety of different model types need to be pulled together and integrated in multi-lateral fashion to properly identify and simulate complex flooding scenarios.

Key Milestones:

Near-Term (0-2 yrs): Identification of needed modeling systems
Mid-Term (2-5 yrs): Loose coupling of selected models
Long-Term (5-10 yrs): Integration of models with development of multi-lateral interactions between models.

USACE POC:
Charles W. Downer, 601.488.9925, Charles.W.Downer@usace.army.mil

Use-Case for Great Lakes Water Level Forecasting and Management

Water-related Challenge(s):

- Recent transition from extreme low water levels to extreme high water levels has resulted in coastal erosion, lakesehore flooding, and exacerbated impacts from coastal storms.
- Regulation of Lake Superior and Lake Ontario outflows aims to maintain natural variability while reducing impacts from extreme levels upstream and downstream.
- Changes in precipitation, runoff, and evaporation require adaptive management.

Context: The Great Lakes basin is home to roughly 20% of the world's surface freshwater, and it is home to about 27 million residents of coastal watersheds. During periods of extreme low water levels, concerns are primarily related to navigation, access to recreation, and drinking water. Extreme high water levels exacerbate issues related to shoreline erosion, coastal flooding, beach hazards, and property damage from coastal storms.

If IHTM capability existed, how could it be used to better address the problem(s)?
Improved seasonal to interannual forecasts of Great Lakes water levels has the potential to improve regulation decisions and adaptive management of the Great Lakes.

Potential Stakeholders: International Joint Commission Boards of Control, navigation, riparians, recreational users of the Great Lakes
Potential "Users" of IHTM Capabilities: USACE, NOAA, academic researchers
Potential "Developers" of IHTM Capabilities: NOAA, USACE, academic researchers

Scientific and Technical Challenges for IHTM Development: Regional climate modeling, prediction in ungaged basins, coupling terrestrial models with lake models, calibration and verification of overlake components of the water balance where virtually no measurements exist, probabilistic forecasting

Impact of IHTM capability to

- *Scientific:* Coupled models that integrate terrestrial runoff with lake thermodynamics and coastal processes
- *Societal:* Improved water level forecasts resulting in more informed regulation decisions and safer use of Great Lakes waters

Contact:
Deborah Lee (deborah.lee@noaa.gov)
Lauren Fry (lauren.fry@noaa.gov)

Key Milestones:
Near-Term (0-2 yrs): Off-line, loose coupling of models
Mid-Term (2-5 yrs): tightly coupled framework
Long-Term (5-10 yrs): operational system that adequately conveys risk for use in water management decisions