INTEGRATED HYDRO-TERRESTRIAL MODELING 2.0:
Progress and Path Forward on Building a National Capability

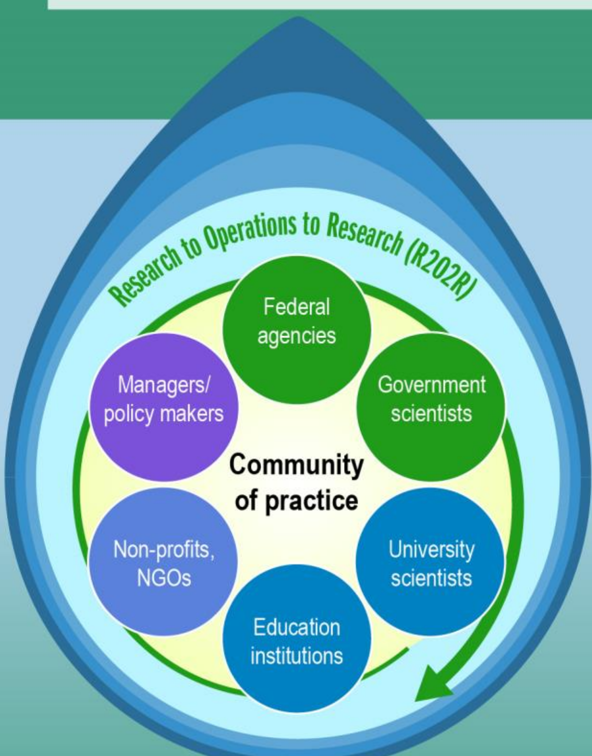
Data management, community platforms, and standards

Software engineering for interoperability and sustainability

Cross-disciplinary workflows: analysis and evaluation

Initial community modeling testbeds

Complex human and natural landscapes



Community Coordinating Group on Integrated Hydro-Terrestrial Modeling

Report of a workshop held October 31-November 2023 with support from participating federal agencies including the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, National Science Foundation, U.S. Department of Energy, U.S. Geological Survey, and the U.S. Environmental Protection Agency, as well as the U.S. Global Change Research Program

AUTHORS

Katie Skalak | Nathalie Voisin | Patrick Reed | Ying Fan Reinfelder

Report prepared January 2025

This article has been peer reviewed and approved for publication consistent with U.S. Geological Survey Fundamental Science Practices (https://pubs.usgs.gov/circ/1367/).

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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PNNL-37047

Integrated Hydro-Terrestrial Modeling 2.0: Progress and Path Forward on Building a National Capability

January 2025

Recommended Citation

Skalak, K., N. Voisin, P. Reed, Y. F. Reinfelder (2025), *Integrated Hydro-Terrestrial Modeling 2.0: Progress and Path Forward on Building a National Capability*. Report of a workshop held October 31-November 2, 2023, with support from participating federal agencies including NASA, NOAA, US EPA USDOE, USGS and the USGCRP. https://doi.org/10.2172/2499550

Report Contributors

Workshop Scientific Organizing Committee

Katie Skalak, U.S. Geological Survey

Nathalie Voisin, Pacific Northwest National Laboratory

Patrick Reed, Cornell University

Ying Fan Reinfelder, Rutgers University

Contributors below listed alphabetically by last name

Workshop Interagency Steering Committee

David Benson, National Oceanic and Atmospheric Administration

Jared Entin, National Aeronautics and Space Administration

Laura Lautz, National Science Foundation

David Lesmes, U.S. Geological Survey

Brenda Rashleigh, U.S. Environmental Protection Agency

Bob Vallario, U.S. Department of Energy

U.S. Global Change Research Program Co-Organizers

Ilana Herold, Social Science Specialist

Yishen Li, Water and Carbon Cycle Science Coordinator

Austin Scheetz, former Social Science Specialist (currently with the National Academies of Science, Engineering, and Medicine)

Invited Workshop Speakers

Alison Appling, U.S. Geological Survey

Rob Cifelli, National Oceanic and Atmospheric Administration

Martyn Clark, University of Calgary

Christopher Dunn, U.S. Army Corps of Engineers

Hedeff Essaid, U.S. Geological Survey

Dave Gochis, National Center for Atmospheric Research

Rob Hetland, Pacific Northwest National Laboratory

John Johnston, U.S. Environmental Protection Agency

Ian Kraucunas, Pacific Northwest National Laboratory

Jacob LaFontaine, U.S. Geological Survey

Debbie Lee, National Oceanic and Atmospheric Administration

Ruby Leung, Pacific Northwest National Laboratory

Jordan Read, Consortium of Universities for the Advancement of Hydrologic Science, Inc.

Lauren Schmied, Federal Emergency Management Agency

Paul Ullrich, Lawrence Livermore National Laboratory

Chris Vernon, Pacific Northwest National Laboratory

Roland Viger, U.S. Geological Survey

Breakout Session Co-Chairs
Nancy Barth, U.S. Geological Survey
Laura Condon, University of Arizona
Ethan Coon, Oak Ridge National Laboratory
Aubrey Dugger, National Center for Atmospheric Research
Lejo Flores, Boise State University
John Hammond, U.S. Geological Survey
Joe Hughes, U.S. Geological Survey
Jeni Keisman, U.S. Geological Survey
Mukesh Kumar, University of Alabama
Lauren Lowman, Wake Forest University
Charlie Luce, U.S. Department of Agriculture
Ryan McGehee, Iowa State University
Venkatesh Merwade, Purdue University
Matt Miller, U.S. Geological Survey
Dave Moulton, Los Alamos National Laboratory
Becca Muenich, University of Arkansas
Scott Painter, Oak Ridge National Laboratory
Yadu Pokhrel, Michigan State University
Limei Ran, U.S. Department of Agriculture
Jodi Ryder, U.S. Army Corps of Engineers
Ben Ruddell, Northern Arizona University
Adam Schlosser, Massachusetts Institute of Technology
Tim Schneider, National Center for Atmospheric Research
Jared Smith, U.S. Geological Survey
Scott Steinschneider, Cornell University
Pamela Sullivan, Oregon State University
Ning Sun, Pacific Northwest National Laboratory
Ahmad Tavakoly, U.S. Army Corps of Engineers
Vincent Tidwell, Pacific Northwest National Laboratory
Jim Yoon, Pacific Northwest National Laboratory

Additional IHTM Testbed Writing Contributors
Yongping Yuan, U.S. Environmental Protection Agency

Acknowledgments

We would like to thank the U.S. Global Change Research Program staff, the Federal Steering Committee agencies (Department of Energy, U.S. Geological Survey, National Science Foundation, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and the Environmental Protection Agency), and ICF for sponsoring and hosting this hybrid workshop.

The workshop organizing committees would like to give special thanks to Gregory Wilson, Ghyslaine Mendez, Alex Da Silva, Fiona Price, Grace Deye, Jasmyn Noel, Valerie Hammer, Scott White, and Peter Schultz of ICF for their roles in planning and facilitating the hybrid meeting format and for their technical support throughout the event, ensuring that the meetings ran smoothly.

The committees would also like to acknowledge and thank an excellent team of workshop website developers and notetakers from the Oak Ridge Associated Universities Oak Ridge Institute for Science and Education: Tracey Vieser, Holly Holt, Natalia Travis, Marci Savoy, Sonia Isotov, and Aiden Layer. They were vital to ensuring a smooth registration process and that discussions in the breakout rooms were properly captured and distilled for subsequent use by all participants and as input to this report.

We would also like to thank the colleague reviewers from USGS, William Farmer and John Bumgarner, and DOE, Jennifer Rice and Vincent Tidwell, for their thoughtful and substantive reviews. Their comments greatly improved the final version of this report.

Finally, the committees thank all plenary speakers and testbed section writers for their contributions and the subsequent Pacific Northwest National Labs (PNNL) production team for making this report a useful and improved final product.

Executive Summary

Water is an essential resource for life. This represents a major U.S. challenge for the twenty-first century, and it is increasingly important to incorporate the human dimensions of freshwater use to understand and predict the availability and quality of freshwater resources. The adaptive management of water resources is crucial for ensuring public health and securing the supply and allocation of water, food, energy, and industrial production to support human well-being, economic growth, and national security while sustaining healthy ecosystems. It is the role of the U.S. federal government and its supporting agencies, including academia and future scientists, to ensure that its people have sustained and equitable freshwater services, as well as the knowledge necessary to make decisions about the future as it relates to freshwater services. Clear and consistent information and guidance from federal agencies is critical.

Integrated Hydro-Terrestrial Modeling (IHTM), as a United States (U.S.) national capability, focuses on understanding, quantifying, and managing the replenishment of water supply through hydrologic cycle processes and their governing forces. IHTM holistically integrates the variation in temporal and spatial distribution of water quantity with knowledge of the quality of water available, clarifying how much is being used and recycled, and growing the vital sources of information that can inform sustainable development and better manage risks.

To provide that information, we need enhanced IHTM capabilities that capitalize on the strengths of each U.S. governmental agency and its core mission. Understanding the likely outcomes of management strategies within a resource-limited future, subjected to pressures from environmental and human changes, requires powerful IHTM capabilities that can assess and assist in the long-term management of water, as well as forecast and mitigate growing risks from increasingly severe and frequent hazards in recent years.

The first IHTM workshop was held in 2019, and its subsequent report was published in 2020. The U.S. Global Change Research Program (USGCRP) and member agencies held a second IHTM workshop (IHTM 2.0) from October 31 to November 2, 2023, in Reston, Virginia. The IHTM 2.0 workshop focused on the need to support a multiscale framework to accelerate research insights, better integrate operational and planning perspectives, and bridge national-to-regional capabilities to address major interdependent societal water challenges. The IHTM 2.0 charge and vision are to:

- Provide updates on emerging IHTM capabilities and research gaps.
- Move from community concepts toward actionable, collaborative testbeds.
- Use the testbeds to accelerate innovations into societally relevant applications.
- Facilitate interagency engagements to inform and strengthen bridges between the research and operational communities (research-to-operations-to-research [R2O2R]).
- Help inform testbeds to explore new approaches and capabilities and enhance capacities through open science principles.

The purpose of this report is to document the discussions held at the workshop, review the roadmap and synthetize actionable next steps. The report is intended to guide researchers across IHTM agencies’ funded projects over the next 3 years toward successful collaborations and investing into long lasting foundational research and systems.

The IHTM 2.0 workshop's structure was carefully organized to draw on the perspectives of the participating U.S. federal agencies and the broader research community. The overall organization of the workshop combined invited plenary speakers and active discussion breakouts to elicit participants' perspectives on emerging IHTM capabilities, gaps, and needs. A multi-agency nomination process selected the invited plenary speakers and co-chairs of the breakout sessions. Session speakers and breakout co-chairs were paired or grouped to specifically bridge the interagency space, enrich the array of topical challenges used to engage attendees, and aid the identification of shared, actionable interests across the testbeds.

IHTM 2.0 focused on five testbeds encompassing the U.S. national scale and four major regional systems (the Mid-Atlantic, Upper Colorado River Basin, the Great Lakes, and Mississippi/Gulf Coast). The national and regional testbeds were selected collaboratively in consultation with the Interagency Steering Committee, the Scientific Organizing Committee, and representatives from the broader suite of USGCRP member agencies.

The plenary presentations and breakout sessions summarized in the report synthesize where we currently are with respect to progress on regional and national testbeds and provide a summary inventory of the capabilities, challenges, and needs. They draw on interactive discussion sessions that further capture the insights and experiences of all IHTM participants. These sessions were faithfully recorded in a set of artifacts: extensive free-form notetaking by external Oak Ridge Institute for Science and Education writers, documents to capture individual responses used to generate collaborative discussions in the sessions, and presentation slides to report out in plenary. Appendix A outlines the plenary insights and resources shared in greater detail.

Section 4.0 offers a synthesis of the aspirational visions for IHTM testbeds, which are expanded for each testbed in Appendix B. A writing team of workshop breakout session leaders was asked to contribute the content based on their synthesis for each of the testbeds' breakout sessions, guided by prompts common to all testbeds to provide consistency.

The workshop was organized according to a "WHAT" and "HOW" framework, with the common underlying "WHY" being the integrated water resource challenges and the "WHO" defined through interagency and cooperating academic partners (Figure ES.1).

Our "WHAT" is providing science, data, and analyses to enable the thoughtful stewardship of our water resources through better-informed decision-making and the accelerated advancement of our understanding and predictive capability of the integrated water cycle, including quality, quantity, use, hydrologic extremes, and human systems. This incorporates the multiscale nature of the problem, from regional to national and over time.

The "WHO" of IHTM is a better community that fosters collaboration and redefines the culture of science through service leadership and open science. An interagency working group is seeking to build a community of practice that covers the R2O2R life cycle with partners in academia and elsewhere. We also seek a direct connection to developing workforce pipelines through training and other means.

"HOW" we will do this is by generating better data and better models through data management, community platforms and standards, software engineering for interoperability (the ability of computer systems and software to exchange and make use of information) and sustainability, and cross-disciplinary workflows. These all ultimately integrate to build place-based testbeds to improve our ability to provide water scenarios to our stakeholders and the public. The testbeds also lead back out in an iterative process to inform our "WHO," "WHAT," "WHY," and "HOW."

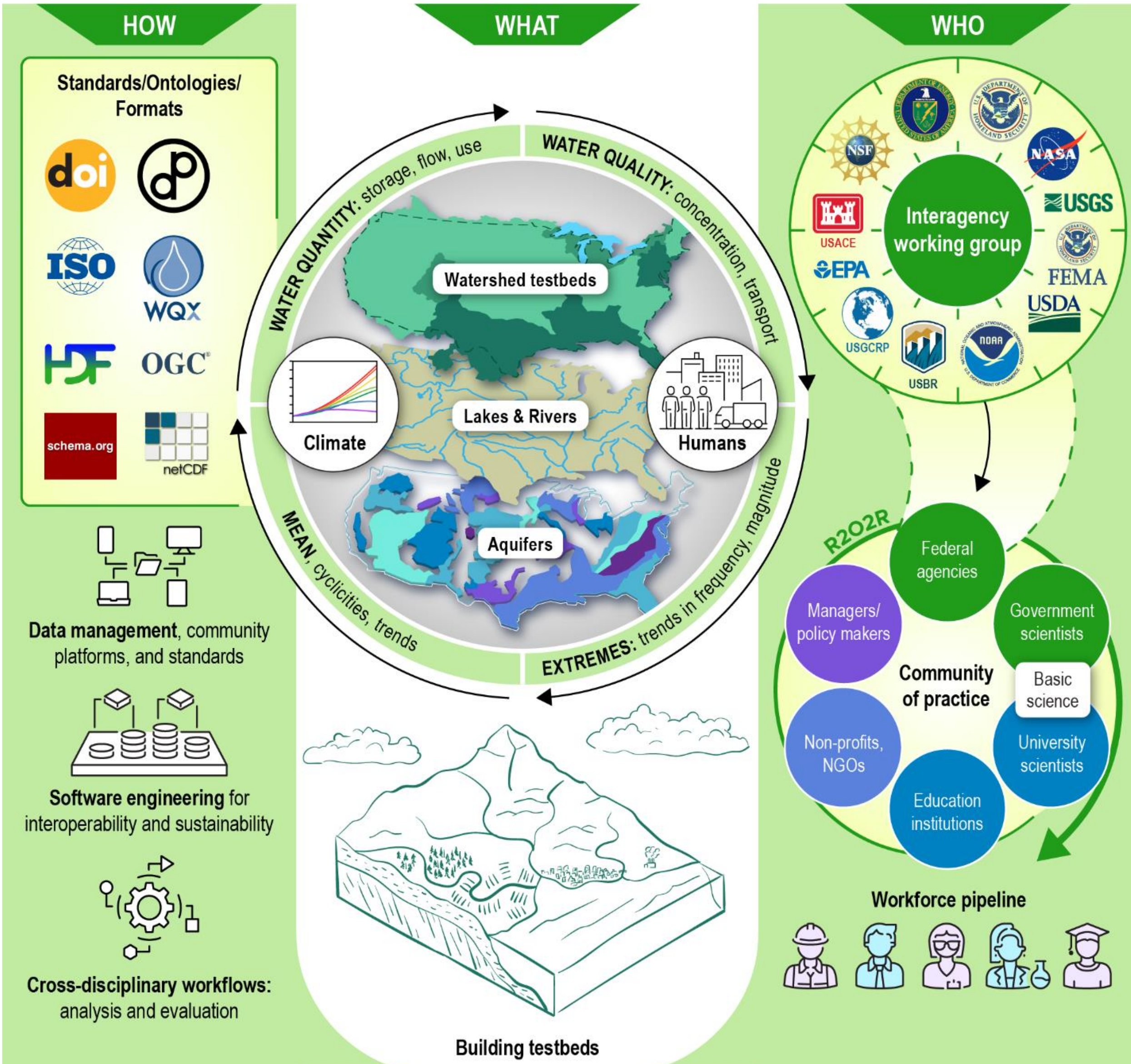


Figure ES.1. IHTM 2.0 advancing on near-term actions developed in IHTM 1.0 through testbed design and co-development and performance strategies (source: Concept – Ying Fan Reinfelder, Design – Nathan Johnson [PNNL]). The IHTM 2.0 framework depicts three lines of efforts, WHAT, HOW, and WHO.

A key lesson learned from IHTM 1.0 is to keep goals tractable and focused. The IHTM 2.0 road map (Section 5.0) focuses on near-term activities that will drive the community forward. Some key activities include the following:

- Continue to elevate community modeling activities at professional organization meetings.
- Organize joint workshops and webinars.
- Establish the IHTM community portal to serve as a hub for building a community of practice.

- Initiate computational experiments in the national and key regional testbeds.
- Organize efforts around areas of significant federal investment, such as enterprise data or models.
- Continue reflecting on the value, need, and impact of IHTM and consider how IHTM computational experiments could inform various national assessments.

Acronyms and Abbreviations

AI	artificial intelligence
CGEM	Coastal Generalized Ecosystem Model
CMAQ	Community Multiscale Air Quality
COMPASS	Coastal Observations Mechanisms and Predictions Across Systems and Scales
CONUS	contiguous United States
CoP	community of practice
CSDMS	Community Surface Dynamics Modeling System
CWMS	Corps Water Management System
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
DOE	Department of Energy
EPA	U.S. Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
FAIR	Findability, Accessibility, Interoperability, and Reusability
FEMA	Federal Emergency Management Agency
GLR	Great Lakes region
H2US	Humans and Hydroclimate in the United States
HAB	harmful algal bloom
HEC	Hydrologic Engineering Center
HUC	hydrologic unit code
HyTEST	Hydro-Terrestrial Earth Systems
ICOM	Integrated Coastal Modeling
IHTM	Integrated Hydro-Terrestrial Modeling
LLNL	Lawrence Livermore National Laboratory
MGC	Mississippi/Gulf Coast
ML	machine learning
MRB	Mississippi River Basin
MSD	Multisector Dynamics
MSD-LIVE	Multi-Sector Dynamics Living Intuitive Value-adding Environment
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NHGF	National Hydrologic Geospatial Fabric
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
ORISE	Oak Ridge Institute for Science and Education
PNNL	Pacific Northwest National Laboratory

PUMP	Predictive Understanding of Multiscale Processes
R2O2R	Research-to-Operations-to-Research
SPLASH	Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology
SWAT	Soil & Water Assessment Tool
TRL	technology readiness level
UCRB	Upper Colorado River Basin
U.S.	United States
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WRF	Weather Research and Forecasting

Contents

Acknowledgments ... iv
Executive Summary ... v
Acronyms and Abbreviations ... ix
1.0 Introduction: Mission and Motivation ... 1
2.0 Background on the Integrated Hydro-terrestrial Modeling Workshops ... 3
3.0 Emerging IHTM Capabilities, Gaps, and Needs for Testbeds from Plenary Talks and Breakouts ... 8
3.1 Context, Capabilities, Gaps, and Needs for the Testbeds ... 9
3.1.1 National Testbed ... 9
3.1.2 Mid-Atlantic Region Testbed ... 11
3.1.3 Upper Colorado River Testbed ... 13
3.1.4 Great Lakes Testbed ... 14
3.1.5 Mississippi/Gulf Coast Testbed ... 16
3.2 Topical (WHAT) and Methodological (HOW) Challenges of IHTM ... 18
4.0 Aspirational Visions for IHTM Testbeds ... 25
5.0 Key Next Steps and the IHTM Roadmap ... 27
5.1 Near-term Opportunities ... 28
5.1.1 Leveraging Scientific Meetings for Community Building ... 28
5.1.2 Collaborative Modeling Efforts and Resource Sharing ... 29
5.1.3 Opportunities to Leverage Funding ... 30
5.2 Medium-term Actions ... 31
5.3 IHTM 2.0 Roadmap ... 32
Appendix A – Plenary Discussions ... A.1
Appendix B – Testbed Visions and Next Steps ... B.1
Appendix C – Workshop Agenda ... C.1
Appendix D – Workshop Participants ... D.1

Figures

Figure ES.1. IHTM 2.0 advancing on near-term actions developed in IHTM 1.0 through testbed design and co-development and performance strategies (source: Concept – Ying Fan Reinfelder, Design – Nathan Johnson [PNNL]). The IHTM 2.0 framework depicts three lines of efforts, WHAT, HOW, and WHO. ... vii

Figure 1.1. The water cycle (source: https://www.usgs.gov/media/images/water-cycle-png). ... 1

Figure 2.1. IHTM 2.0 advancing on near-term actions developed in IHTM 1.0 through testbed design and co-development and performance strategies (source: Concept – Ying Fan Reinfelder, Design – Nathan Johnson [PNNL]). It depicts three lines of efforts, WHAT, HOW, and WHO, converging on the goal of building actionable testbeds, represented by the bottom-center graphic. The cycle under WHAT represents the hydrologic variables that IHTM endeavors to predict under a changing climate and human forces, including surface and groundwater quantity and quality. The left HOW column represents the technological and operational advances needed to develop IHTM capabilities. The right WHO column represents the Community of Practice to develop and sustain IHTM, with the upper wheel depicting the coordinated efforts among the federal agencies in an Interagency Working Group. This interagency wheel is the central component of the lower wheel, powered by R2O2R knowledge flows, involving basic research and operational communities and engaging stakeholders. The gap in the R2O2R cycle symbolizes an entrance for future workforces. Test beds are central for the joint development and applications of the concepts and protocols. 5

Figure 2.2. (A.) Image of the ICF meeting facility that enabled the successful hybrid participation of more than 160 people. (B.) Image of in-person workshop attendees at the ICF facility (source: Y. Li). 6

Figure 2.3. (A.) Image of the participants in-person and hybrid on the computer screen at the back wall for the Great Lakes breakout session. (B.) Image of in-person participants for the Mississippi/Gulf Coast breakout session (this session was also hybrid, but virtual participants are not visible in the image) (source: Y. Li). 7

Figure 3.1. The five testbeds: National CONUS, Upper Colorado, Mississippi/Gulf Coast, Mid-Atlantic, Great Lakes. National and Mississippi Gulf Coast encompass multiple major river basins (hydrologic unit code 2) (source: N. Voisin). 9

Figure 3.2. Simplified readiness level roadmap to clarify R2O2R opportunities across agencies; opportunities will highlight clear understanding of the readiness levels (source: NOAA readiness levels, adapted by N. Voisin). 16

Figure 3.3. Attributes of success for test beds to realize major societal benefits (source: A. Appling). 19

Figure 3.4. NHGF provides a common base for generating spatial modeling units (source: R. Viger). 22

Figure 5.1. Examples of programs at the National Science Foundation, as of December 2024, that support research and cyberinfrastructure development with Earth Sciences, the Geosciences Directorate, and across the Foundation. 30

Figure 5.2. IHTM 2.0 Roadmap starting in 2024 with the release of the IHTM 2.0 workshop report. High-level interagency priority activities are shown on the top line by year, including computational experiments, organizing around federal assets, model benchmarking, and a possible contribution to future National Climate Assessments (NCAs) through existing computational experiment outputs by 2028. Ongoing maintenance activities are shown on the bottom line, including the establishment of the

portal style and rhythm, engagement with scientific societies, initiation of the technical CoP, and an evaluation of all IHTM elements before a proposed workshop in 2028. 35

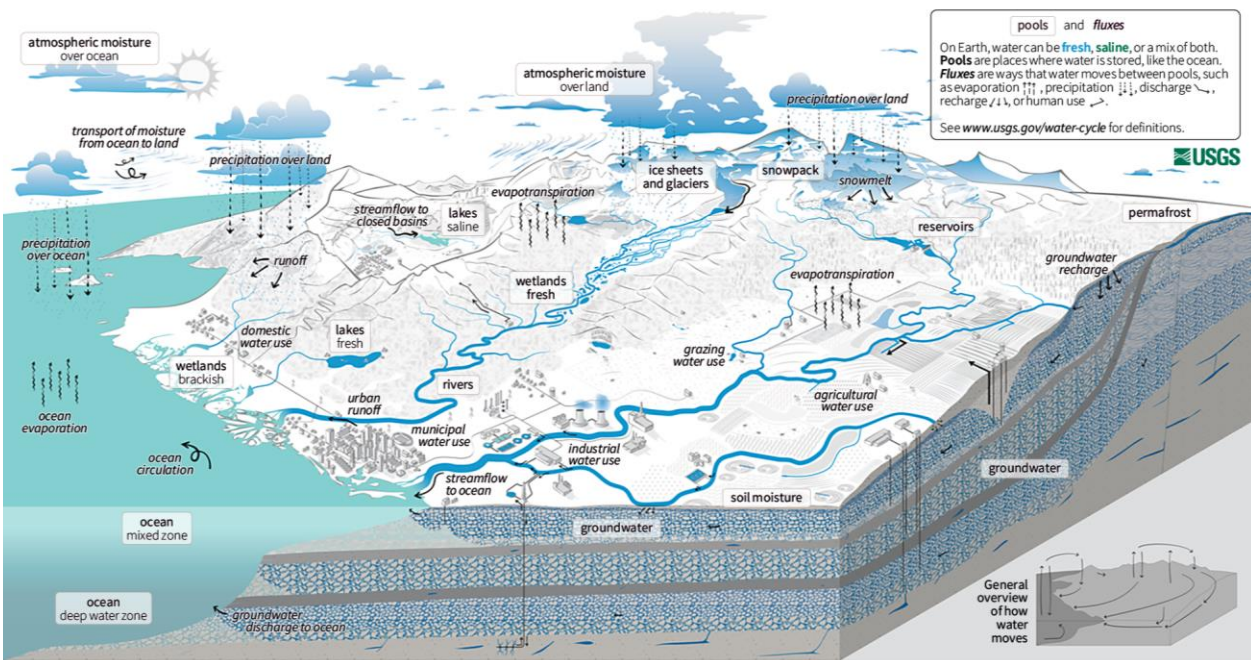
Figure A.1. Core components of water availability in the USGS Water Resources Mission Area (source: Adapted by J. Lafontaine, Design – Nathan Johnson). A.3
Figure A.2. Coordinated research under the new Global Energy and Water Exchanges (GEWEX) Humans and Hydroclimate in the United States (H2US) Regional Hydroclimate Project (source: T. Schneider and R. Cifelli). A.7
Figure A.3. Integrated Multimedia Modeling Framework designed to address effects of land use/land management and climate changes on nutrient loss (source: Ran et al., 2019, Figure 1). A.11
Figure A.4. Changes in climatic drivers affect the hydrologic cycle, which translates into changes in different drought types (source: IPCC AR6 WG1, chapter 6, adapted by R. Leung). A.13
Figure A.5. Principles of a CoP. IHTM, whether a distinct and/or subset of existing CoPs, would help address the pressing needs of the nation (source: J. Read, adapted by N. Voisin). A.16
Figure B.1. Core components of the national testbed include forcings, infrastructure, data, and standards and governance. Key models for a national testbed include hydrologic, ecosystem, socioeconomic, and climate models (source: A. Dugger and the national testbed group). B.3
Figure B.2. The timescale on which research insights are generated operates independent of decision timescales. An adaptive, iterative R2O2R process allows insertion of new insights into operational decision-making frameworks as they emerge (source: J. Keisman). B.7
Figure B.3. R2O2R framework applications in the Great Lakes Regional testbed (source: R. Muenich and GLR testbed group). B.12
Figure B.4. R2O2R cycle for the Mississippi/Gulf Coast testbed (source: J. Ryder and MGC Testbed Group). B.15
Figure B.5. An application of the Integrated Multimedia Modeling Framework for the Mississippi River Basin/Gulf Coast (source: Yuan et al., 2018; Ran et al., 2019; Jarvis et al., 2024). B.17

Tables

Table A.1. New climate data products over CONUS (source: P. Ullrich, access or information compiled by I. Herold). A.2

1.0 Introduction: Mission and Motivation

Water is essential for the continuation of life on Earth and one of our most critical natural resources. It shapes Earth's surface and controls where and how we live. There are many significant U.S. water challenges related broadly to increasing demands to support critical uses, the changing nature of the hydrologic cycle and changing climate, and other environmental pressures that degrade the quality of available water resources. The challenges in meeting diverse and often competing water demands are increasing. The locations and variability of these demands are often not well aligned with the availability of supply, requiring significant infrastructure and energy to move and store water. Hydrologic extremes, such as droughts and floods, exacerbate these disparities. Droughts can lead to costly water shortages and infrastructure damages, and floods have led to loss of life and infrastructure. The adaptive management of water resources in the face of these issues is crucial for ensuring public health and securing the supply and allocation of water, food, energy, and industrial production to support human well-being, economic growth, and national security, while sustaining healthy ecosystems. This represents a major U.S. challenge for the twenty-first century, and it is increasingly important to incorporate the human dimensions of freshwater use to understand and predict the availability and quality of freshwater resources (Figure 1.1).



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It is the role of the U.S. federal government and its supporting agencies, including academia and future scientists, to ensure that its people have sustained and equitable freshwater services, as well as the knowledge necessary to make decisions about the future as it relates to freshwater services and subsequent health, environmental, safety, equity, energy, and economic implications. Clear and consistent information and guidance from federal agencies is critically necessary. Integrated Hydro-Terrestrial Modeling (IHTM) as a United States (U.S.) national capability, provides that information. IHTM capabilities capitalize on the strengths of each U.S. governmental agency and their core mission which are needed to understand, quantify, and manage the replenishment of water supply through hydrologic cycle processes and their governing forces. It is critical that IHTM holistically integrates this understanding across U.S. governmental agencies with knowledge of the quality of water available, clarifying how much is being used and recycled, and growing the vital sources of information that can inform sustainable development and better manage risks.

Understanding the likely outcomes of management strategies within a water resource-limited future subjected to pressures from environmental and human changes requires powerful IHTM capabilities that can assess and assist in the long-term management of water, as well as forecast and mitigate the growing risks from increasingly severe hazards that are being experienced more frequently in recent years.

The efficient development and sustained operation of a national water prediction and projection capability requires interagency coordination, the effective use of resources (e.g., financial, computing, data, training material, and workforce), and an approach for incorporating community research advances. These needs motivated the first IHTM workshop in 2019 (IHTM 1.0, below) and continuing multi-agency initiatives. To better understand the progress that has been achieved since the first IHTM workshop, further facilitate effective integration of existing water prediction capabilities, and aid the coordination of continued future efforts, the IHTM 2.0 workshop was held in October 2023 in Reston, Virginia, at ICF Headquarters. Each of the participant agencies in the IHTM 2.0 workshop is responsible for distinct scientific research and/or operational missions that advance the nation’s ability to address water-related problems. However, the research and operational challenges often span the missions of multiple agencies, and, thus, their solutions require the combined research, resources, and expertise of several agencies and academia. Through integrating the expertise and capabilities of the full U.S. water research and operations enterprise, IHTM has the potential to better capture complex Earth systems and human behavior for improved understanding and decision-making. IHTM offers a platform that could ideally support the various operational and educational needs of the water mission agencies and yield solutions to water-related problems at multiple scales and accelerate science in service to the nation.

The purposes of this report are to summarize previous IHTM efforts (IHTM 1.0), document the discussions held at the IHTM 2.0 workshop, review the roadmap and synthesize actionable next steps. For the purpose of emphasizing the roadmap and next steps, the summary of plenary presentations and the vision of potential collaborations across agencies through testbeds, all developed by participants, can be found in Appendix A and Appendix B. The main report provides a synthesis of those visions using testbed protocols. The report is intended to guide researchers across IHTM agencies’ funded projects over the next 3–5 years toward successful collaborations and toward investing into long lasting foundational research and tools.

2.0 Background on the Integrated Hydro-terrestrial Modeling Workshops

IHTM 1.0: The first IHTM workshop was held in September 2019 at the National Science Foundation (NSF). Four interagency leads from U.S. Geological Survey (USGS; David Lesmes), NSF (Tom Torgersen), and Department of Energy (DOE; Bob Vallario and Jessica Moerman) brought together an Interagency Steering Committee of representatives from the DOE, Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), NSF, U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), U.S. Global Change Research Program (USGCRP), and USGS and three workshop co-chairs from academia and government—Tim Scheibe (Pacific Northwest National Laboratory [PNNL]), Efi Foufoula-Georgiou (University of California-Irvine), and Harry Jenter (USGS)—to lead 120 workshop participants.[1] The participants represented multiple agencies with water-related missions, as well as the academic science community who worked collaboratively to develop the initial vision for advancing U.S. IHTM capabilities. The mission of the IHTM initiative was to meet the needs put forward in the Priority Water Challenges,[2] which were identified as excess nutrients, hypoxia, and harmful algal blooms; extreme weather-related water hazards; and water availability in the western U.S. These challenges helped identify critical needs in four key technical areas, including 1) data management, community platforms, and standards, 2) analysis and evaluation of cross-disciplinary workflows, 3) software engineering for interoperability and sustainability, and 4) building computational testbeds.

The effort was essentially a pathfinder toward synergistic priorities, multi-agency data, and simulation capabilities and products that provide the basis for understanding and managing complex water systems within a research-to-operations-to-research (R2O2R) framework. The close relationship between water research and operations relates to translating advances in predictive capability to inform actual water management decisions; it has been referred to as the "research to operations [R2O] pipeline." Likewise, operations have an important role in informing research needs, thus motivating the broader concept of the "R2O2R pipeline" for effective water management. This coordination between scientific research, training, operational prediction, and resource management can provide the basis to solve societal problems based on actionable intelligence through continuous advancement of scientific understanding. Prediction capabilities must be flexible to accommodate advances in scientific understanding and technology. Key goals from the first IHTM workshop included enhancing a national capability for prediction and scenario-building; advancing the water-related missions (both collectively and individually) of the water mission agencies, and advancing science through integration of the best available process understanding.

IHTM 1.0 identified a pathway for a sustainable community, which included simultaneous advancements in the near term (months to a year), medium-term (2–5 years), and long term

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[1] Community Coordinating Group on Integrated Hydro-Terrestrial Modeling. 2020. "Integrated Hydro-Terrestrial Modeling: Development of a National Capability." Report of an Interagency Workshop held September 4–6, 2019, with support from the National Science Foundation, the U.S. Department of Energy, and the U.S. Geological Survey. https://doi.org/10.25584/09102020/1659275.

[2] NAS. 2018. *Future Water Priorities for the Nation: Directions for the US Geological Survey Water Mission Area*. National Academies of Sciences, Division on Earth, Life Studies, Water Science, Technology Board, Committee on Future Water Resource Needs for the Nation, Water Science, and Research at the U.S. Geological Survey. National Academies Press.

(> 5 years). Examples of near-term efforts included the creation of a multi-agency working group to generate community buy-in and create incentives, collectively co-design pilot efforts, and focus on early wins using flexible approaches. Medium-term efforts included determining and implementing common data and model standards through the creation of communities of practice, as well as interagency coordination on mission alignment, business, and funding practices. Long-term pathways included transforming the research and operational community culture toward sharing data, co-developing models, and generating timely, coordinated forecasts for stakeholders, as well as having the agencies move toward evolving their business and funding practices for mission alignment and optimal impact. Considerable progress on near-term and some medium-term priorities have been achieved since IHTM 1.0. Many agencies internally adopted standards that are now recognized as part of the community and several agencies formed smaller partnerships that have made community progress possible. However, a significant portion of the IHTM 1.0 roadmap is not yet done (discussed further in Section 5.0) and the community has work to do.

Coastal IHTM: Building on the success of IHTM 1.0 in 2019, in November 2020, a follow-on Coastal IHTM workshop was held virtually and chaired by Bob Vallario (DOE), Jeffrey Arnold (USACE), and John Weyant (Stanford). With more than 20 session co-chairs spanning several federal agencies and academic institutions, the workshop hosted approximately 200 participants from DOE; EPA; USACE; NASA; National Institute of Standards and Technology; NOAA; National Park Service; NSF; Office of Naval Research; USDA; USGCRP; USGS; Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI); and 25 universities. The sessions focused on facilitating reproducibility and extensibility; coastal use cases such as the Chesapeake Bay and Mississippi Gulf Coast; integrating modeling frameworks to encompass the atmosphere, ocean, land, and human systems; continuing efforts toward developing a community of practice; and specific topical areas such as water quality, coastal retreat, and model evaluation.

IHTM 2.0: The October 2023 IHTM 2.0 workshop emerged from sustained progress and efforts since the IHTM 1.0 and Coastal IHTM workshops within single agencies, between two partner agencies, and among multiple agencies. The USGS hosted a cross-agency workshop with U.S. Bureau of Reclamation (USBR) in September 2020, which led to significant collaborative opportunities for integrated modeling within the Delaware River Basin that directly drew on the principles and needs put forward in the first IHTM workshop and incorporated a high level of academic partnership. USGS and NOAA have also participated in continued discussions and agreed to collectively advance a standardized Basic Model Interface (BMI) strategy to better support coupling of key models. BMI is a set of standard query and control functions that, when added to a model code, make that model both easier to learn and easier to couple with other software. This was developed by the Community Surface Dynamics Modeling System (CSDMS).The national hydrological geospatial fabric (NHGF) was co-developed by NOAA and USGS and forms the basis for the national modeling efforts of both agencies. The hydrofabric is a dataset containing a network of connected representations of rivers, lakes, and catchments. A hydrofabric is purpose-built, meaning that the choices about the representation of rivers, lakes, and catchments with spatial and attribute information are for a specific purpose. The national hydrofabric from USGS and NOAA efforts is meant to support national hydrologic modeling. This is also often referred to as a geospatial fabric and, in the context of this report, the terms are used interchangeably.

DOE and USGS have partnered with academia in a few basins across the country to continue to advance IHTM efforts along water availability assessments, such as inventories of water withdrawals for the electricity sector (thermoelectric plants) and water security in general (bottled water), and on water availability multi-model projections across the contiguous United States (CONUS) with associated analytics to understand the contributions of model structure, model parameterization, and observations to the quantified uncertainties.

The IHTM 2.0 workshop drew on these efforts to focus on designing and supporting a multiscale framework (Figure 2.1) to accelerate the exchange of research insights and associated data and tools, the integration of operational perspectives, and the bridging of national-to-regional capabilities to address the nation's major interdependent water challenges. Scheduled over 2.5 days, the workshop provided a fully hybrid experience for over 160 attendees (Appendix C and Appendix D), of which approximately 60 participated virtually (Figure 2.2).

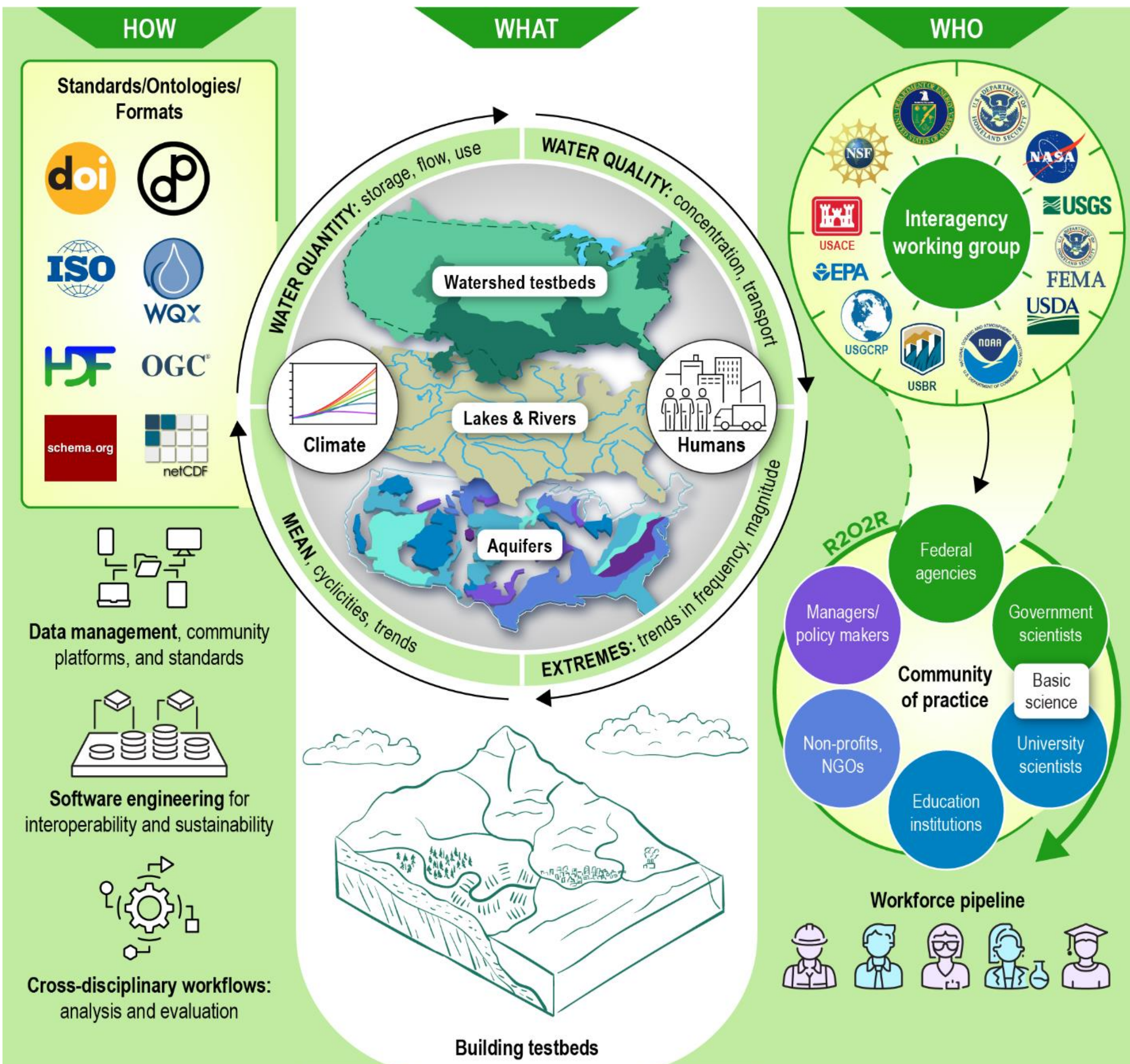

Figure 2.1. IHTM 2.0 advancing on near-term actions developed in IHTM 1.0 through testbed design and co-development and performance strategies (source: Concept – Ying Fan Reinfelder, Design – Nathan Johnson [PNNL]). It depicts three lines of efforts, WHAT, HOW, and WHO, converging on the goal of building actionable testbeds, represented by the bottom-center graphic. The cycle under WHAT represents the hydrologic variables that IHTM endeavors to predict under a changing climate and human forces, including surface and groundwater quantity and quality. The left

HOW column represents the technological and operational advances needed to develop IHTM capabilities. The right WHO column represents the Community of Practice to develop and sustain IHTM, with the upper wheel depicting the coordinated efforts among the federal agencies in an Interagency Working Group. This interagency wheel is the central component of the lower wheel, powered by R2O2R knowledge flows, involving basic research and operational communities and engaging stakeholders. The gap in the R2O2R cycle symbolizes an entrance for future workforces. Test beds are central for the joint development and applications of the concepts and protocols.

Figure 2.2. (A.) Image of the ICF meeting facility that enabled the successful hybrid participation of more than 160 people. (B.) Image of in-person workshop attendees at the ICF facility (source: Y. Li).

The USGCRP, NSF, NASA, NOAA, DOE, and USGS composed the Interagency Steering Committee and, overall, 11 U.S. federal agencies participated in the workshop. Participants also included representatives from 27 academic institutions, and private entities, including CUAHSI. The workshop provided an exciting forum for a broad representation of the emerging IHTM community to provide updates on emerging IHTM capabilities since the first workshop, identify critical research gaps that still exist, and define synergistic coordination strategies to address those gaps through breakout sessions (Figure 2.3). The goal for the IHTM 2.0 workshop was to continue to advance by moving beyond defining foundational concepts and toward actionable collaborative testbeds.

Building on the progress made since IHTM 1.0, the IHTM 2.0 workshop aimed to use the testbeds to accelerate innovations into societally relevant applications and facilitate sustained interagency engagements to inform and strengthen bridges between the research and operational communities (R2O2R). There is still work to be done to effectively collaborate across the interagency space: the second workshop—described in this report—aimed to help inform testbeds to explore new approaches, capabilities, and enhance capacities through open science principles and workforce training and coordination.

Figure 2.3. (A.) Image of the participants in-person and hybrid on the computer screen at the back wall for the Great Lakes breakout session. (B.) Image of in-person participants for the Mississippi/Gulf Coast breakout session (this session was also hybrid, but virtual participants are not visible in the image) (source: Y. Li).

3.0 Emerging IHTM Capabilities, Gaps, and Needs for Testbeds from Plenary Talks and Breakouts

The IHTM 2.0 workshop's structure was carefully organized to draw on the perspectives of the participating U.S. federal agencies and the broader research community. The overall organization of the workshop combined invited plenary speakers and active discussion breakouts to elicit participants' perspectives on emerging IHTM capabilities, gaps, and needs. A multi-agency nomination process selected the invited plenary speakers and co-chairs of the breakout sessions. Session speakers and breakout co-chairs were paired or grouped to specifically bridge the interagency space, enrich the array of topical challenges used to engage attendees, and aid the identification of shared, actionable interests across the testbeds. The detailed workshop agenda is provided in Appendix C.

IHTM 2.0 focused on five testbeds encompassing the CONUS national scale and four major regional systems (the Mid-Atlantic, Upper Colorado River, the Great Lakes, and Gulf Coast/Mississippi, Figure 3.1). The national and regional testbeds were selected collaboratively in consultation with the Interagency Steering Committee, the Scientific Organizing Committee, and representatives from the broader suite of USGCRP member agencies with interests in IHTM through the interagency Integrated Water Cycle Group and Coasts Interagency Group. The regional testbeds were selected in locations where existing agency efforts can be leveraged to facilitate IHTM collaborations, their water resources challenges capture the scope of major U.S. concerns, and where there is an abundance of expertise from participating entities (federal, state, local, tribal). The national testbed was selected because of the burgeoning priority of several agencies to provide actionable insights for water across the country. Overall, the testbeds ground the concept of IHTM in societally relevant problems, technological challenges, and opportunities for collaboration among agencies, universities, and regional stakeholders. Showcasing these testbed regions offers the opportunity to demonstrate commonalities and uniqueness among the regions and agencies to align them in a future IHTM framework.

The goal of the IHTM 2.0 workshop's plenary talks was to capture important and potentially shared themes for advancing modeling capabilities, accelerating applications with R2O2R insights, and strengthening interagency engagements. Although the highlighted challenges and needs reflect the rich perspectives of the selected plenary speakers, they should not be seen as an attempt to exhaustively capture all the testbeds' capabilities, challenges, and needs. Building on the motivating perspectives of the plenary speakers, the IHTM 2.0 workshop utilized highly interactive participatory breakout sessions to capture insights, recommendations, and experiences of all the attendees. Brief summaries of the key points from the plenary talks and the subsequent breakout sessions are provided below and in Appendix A.

Figure 3.1. The five testbeds: National CONUS, Upper Colorado, Mississippi/Gulf Coast, Mid-Atlantic, Great Lakes. National and Mississippi Gulf Coast encompass multiple major river basins (hydrologic unit code 2) (source: N. Voisin).

3.1 Context, Capabilities, Gaps, and Needs for the Testbeds

3.1.1 National Testbed

Plenary Speakers: Paul Ullrich (DOE), Jacob LaFontaine (USGS), Brenda Rashleigh (EPA)
Breakout Leads: Laura Condon (University of Arizona), Aubrey Dugger (NCAR)
Testbed Writing Lead authors: Lauren Lowman (Wake Forest University), Yadu Pokhrel (Michigan State University), Laura Condon (University of Arizona), Aubrey Dugger (NCAR), Charles Luce (USDA Forest Service), Tim Schneider (NCAR), Roland Viger (USGS)

Although water resource and integrated community modeling challenges are global, U.S. federal agencies are generally funded to prioritize these issues at a national level. The development of interagency efforts in IHTM using best practices from both the national and global scientific community will enable partnership with international efforts, such as Environment Climate Change Canada among others. The national testbed was selected as an important focus given the major investments and advances in CONUS scale data and modeling capabilities that have emerged across multiple federal agencies since the 2019 IHTM 1.0 workshop.

The U.S. faces a complex set of hydrologic challenges that range from water quantity in arid states that require solutions related to allocation, to water quality in coastal regions where ecological well-being and public health are of great concern. Expertise from multiple sectors (government, academic, private), collaboration with stakeholders (farmers, natural resource managers, landowners, tribes), and interdisciplinary knowledge must be combined to create meaningful and long-lasting solutions. Models are important tools for capturing this diverse knowledge and designing solutions; however, there are several factors limiting our current capabilities. Key national modeling challenges include:

- addressing data-related bottlenecks and improving data availability, accessibility, and accuracy (e.g., bias detection and adjustment, better coordination with climate modeling, and leveraging satellite remote sensing)
- harmonizing and maintaining multiple sets of national-scale spatial data that include varied data types and have the potential to represent relationships and connectivity among spatial features to provide required model inputs across platforms
- achieving accurate predictions of extreme hydrological events and their impacts on human and natural systems
- better integrating human dynamics and operations into hydrologic models
- evaluating both the individual and compounded effects of climate, land use/land cover, and water management changes on hydrologic processes
- considering not only water availability, but also water quality and ecological needs.

In response to these challenges, an IHTM national testbed provides a platform for model documentation, intercomparison, benchmarking, and improvement, helping to ensure the credibility and reliability of current and future model-based solutions to our nation's water challenges. Furthermore, the IHTM national testbed could serve as a central hub to bring sectors and disciplines together, providing a systematic framework to address methodological gaps and evaluate hydrologic challenges across scales. The national testbed must be responsive to a broad set of human and environmental needs by understanding and engaging with diverse stakeholders. Given the growing number of hydrologic models that can operate at national scales, reducing redundancy and improving efficiency are important testbed goals. However, it is often model mischaracterization and misuse ("fit for a different purpose") that threaten the loss of public trust. It is critical that government agencies, supported by academic partners, serve as definitive sources of credible and reliable information for addressing hydrologic challenges.

The plenary speakers in the national session of the workshop identified critical areas of focus for IHTM at this scale including: 1) the need for appropriate and relevant climate information including downscaled climate model output, common evaluation standards, and better guidance for climate data product use by connecting to user needs (see strategies in Box 1 below), 2) national scale hydrologic modeling efforts focused on water quantity, water quality, and water use that can provide a host of collaborative opportunities through shared computing environments, common scenarios and forcings, open data management and processing capabilities, geospatial fabrics, process representation, and R2O2R governance, 3) examples of specific modeling frameworks including the National Hydrologic Model (NHM), the National Water Model (NWM), Visualizing Ecosystem Land Management Assessments (VELMA) Ecohydrology Model, the integrated assessment modeling framework with the Hydrologic and Water Quality System linked with the Benefits Spatial Platform for Aggregating Socioeconomics and H2O Quality (HAWQS-BENSPLASH), and Water Analysis and Simulation Program (WASP) (see more in Appendix A).

From the breakout report out for the National Testbed, highly valued emerging IHTM capabilities include geospatial fabrics, new computing infrastructures, better integrated software development practices for modeling frameworks, enhanced plug-and-play integration across models, new observational datasets (e.g., the Airborne Snow Observatory), and the ability to expand environmental and social justice applications. The largest identified gaps lie in coordination due to challenges associated with agency silos, gaps between data collectors and modelers, diffuse leadership and governance with no clear community of practice, and incentives to develop “off-the-shelf” capabilities that have a clearer connection to the R2O2R pipeline. At the national scale, a core need is the availability of credible models capable of predicting hydrologic conditions in normal and extreme conditions while considering human operations and changing conditions. There is a need to better address questions people care about by improving the decision relevance and operational value of modeling efforts. The U.S. government agencies should be a definitive source for national-scale credible and reliable hydrologic information.

Regional Testbeds

The four regional testbeds were selected with feedback from the federal agencies’ representatives to capture the broad array of challenges facing different U.S. water regions, as well as for their potential for actionable collaboration opportunities. The selected testbeds offer the potential to leverage a substantial number of currently independent agency efforts. They each encompass a substantial body of existing work and offer unique capabilities that, when thoughtfully integrated across agencies, can significantly accelerate needed progress in addressing regional challenges.

3.1.2 Mid-Atlantic Region Testbed

Plenary Speakers: *Hedeff Essaid (USGS) and Ian Kraucunas (PNNL)*
Breakout Leads: *Jeni Keisman (USGS) and Ning Sun (PNNL)*
Testbed Writing Lead authors: Scott Steinschneider (Cornell University), Jared D. Smith (USGS), Jim Yoon (PNNL), Ning Sun (PNNL), Jeni Keisman (USGS)

The region defining the Mid-Atlantic U.S. at its most encompassing definition includes New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia, West Virginia, and Washington, DC. This region is one of the most densely populated of the country, with multiple major coastal metropolitan areas and a population exceeding 60 million people (almost 20 percent of the entire U.S. population). The Mid-Atlantic region is also home to a large agricultural sector, particularly in Pennsylvania, New York, and the DelMarVa Peninsula. Together, agriculture in the Mid-Atlantic region consists of approximately 28.7 million acres of farmland producing approximately $17.2B in agricultural receipts annually. These characteristics make the Mid-Atlantic region a unique setting to investigate key IHTM capabilities at the rural-urban and urban-coastal nexuses.

There are several critical hydrologic challenges facing the Mid-Atlantic, although these challenges vary across the region’s major river basins, which include the Hudson, Delaware, Susquehanna, and Potomac. Across the entire Mid-Atlantic region, observed and projected increases in extreme precipitation and flood risk are a major cause of concern, particularly in coastal areas exposed to tropical cyclones where compound flooding linked to co-occurring heavy rainfall, riverine flooding, and storm surge threatens dense population centers such as Philadelphia and Baltimore.

More generally, heightened hydrologic variability linked to climate change is driving water availability concerns. Despite the region's abundant precipitation compared to other areas of the country, global climate models suggest an increasing trend in the frequency of flash droughts, as well as compound drought and heatwaves. This can create significant challenges in managing water resources for dense population centers and ecosystems in this region where sectoral water supply has evolved in a water-abundant environment. Compounding these challenges is the region's water supply and flood protection infrastructure, much of which is aging and deficient.

In coastal basins of the Mid-Atlantic, the increasing hydrological variability is also intensifying concerns about water quality. Saltwater intrusion, exacerbated by rising sea levels and periods of drought when freshwater input to estuaries is low, is driving growing concerns about water quality in both riverine surface waters, as well as groundwater used for public drinking water supplies. Salinization is further exacerbated by extensive road salt and deicer application throughout urban and suburban communities, which can threaten water quality in the headwater regions of major river basins. In other basins, like the Susquehanna, which drains large agricultural areas within the Mid-Atlantic, sediment and nutrient export are major concerns due to annually occurring coastal hypoxia, harmful algal blooms, and dead zones in the Chesapeake Bay.

The plenary speakers highlighted important existing capabilities including but not limited to Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA, NOAA), Coastal Observations Mechanisms and Predictions Across Systems and Scales (COMPASS, DOE), Integrated Coastal Modeling (ICOM, DOE), and the Predictive Understanding of Multiscale Processes (PUMP) project of the Integrated Water Prediction Program (PUMP, USGS). Among these efforts, ICOM and PUMP were showcased for IHTM capabilities. ICOM is focused on long-term scenarios that include climate and land use interactions, hydroextremes, hypoxia, and hazards associated with sea-level rise. The PUMP project focuses on using downscaled climate products forcing subsetted national hydrological models that are loosely coupled with regional groundwater models, process-guided machine learning models for water quality, reservoir models, and models for estuary salinity and hydrodynamics.

The breakout report out for the Mid-Atlantic indicates that the region has an extremely rich set of existing models and data. There is a strong potential to leverage cross-agency modeling efforts for hurricanes, floods, droughts, salinity intrusion into coastal aquifers, water quality, ecosystems health, and long-term water availability assessments given climate change and growing multi-sectoral demands. One of the largest identified gaps is the general lack of awareness and coordination of IHTM-relevant efforts across institutions, agencies, and researchers. As an example, the Chesapeake Bay Model Inventory and Selection Tool by itself identifies more than 100 models addressing concerns from watersheds to the coastal estuary. There are also a broad range of data gaps related to human demands, water quality, and water management operations. The Mid-Atlantic breakout further identified a critical need to enhance IHTM capability outcomes and give Mid-Atlantic decision-makers a better understanding of the utility and cost-effectiveness of management options for regional planning, management of evolving hazards, and improvement of water quality and ecosystem services holistically. Interagency efforts are needed to include shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and improved open science protocols.

3.1.3 Upper Colorado River Testbed

Plenary Speakers: *Dave Gochis (NCAR) and Rob Cifelli (NOAA)*
Breakout Leads: *Lejo Flores (Boise State University) and Ben Ruddell (Northern Arizona University)*
Testbed Writing Lead authors: Alejandro Flores (Boise State University), John Hammond (USGS), Matt Miller (USGS), David Moulton (Los Alamos National Laboratory), Ben Ruddell (Northern Arizona University), Vincent Tidwell (PNNL)

The Colorado River Basin occupies an area of approximately 250,000 square miles and supplies water to seven basin states (Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming) and approximately 40 million people. The Colorado River originates along the Continental Divide in Rocky Mountain National Park, Colorado, and ends where it meets the Gulf of California in Mexico. The Upper Colorado River Basin (UCRB) is defined by the river network above Lees Ferry in northern Arizona. The UCRB contributes the vast majority of the water coming into the Colorado River Basin, primarily through winter snowpack. The Colorado River Basin is a basin in crisis, with every drop of water in the Colorado River allocated and climate change increasing aridification. Aging water resource management infrastructure, increasing complexity in water demand and use, and the rigidity of water rights frameworks that govern water allocation (and differ between riparian zones) all introduce boundary conditions that constrain the ability to find innovative solutions to water scarcity and quality issues in the basin. The intersection of these pressures from both natural and human system realms lead to pressure on the UCRB, the natural seasonal reservoir of water for the Colorado River Basin.

This context makes the opportunities and challenges of IHTM efforts clear within the UCRB. There is a pressing scientific and societal need to simultaneously (1) address knowledge gaps in physical process understanding of how the water cycle in the UCRB is changing across a range of spatiotemporal scales, (2) foster effective working relationships with managers to understand data and information needs that increasingly cannot be met by their current toolset, and (3) rapidly develop new or augment existing tools, datasets, and information that fill unmet data, information, and knowledge gaps of managers in reliable and trustworthy ways. At the same time, immense regional investments across key stakeholders (e.g., states, municipalities, tribes, etc.) and federal agencies like DOE, USGS, NOAA, USDA, and the USBR around the broader issue of water in the UCRB have created timely opportunities for IHTM efforts to make substantive progress toward these imperatives.

The plenary talk highlighted that there are several major R2O2R efforts that are ongoing in the UCRB related to improving prediction of weather and water in the complex, mountainous terrain of the basin including the Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) and the recent emergence of major water prediction and assessment capabilities in the UCRB. Several key challenges are also highlighted including issues with forcing observations, uncertainty of seasonal forecasts, and operationalizing emerging observational field campaigns. Other major IHTM challenges in the UCRB include capturing human system components such as reservoir management, agriculture and urbanization as well as disturbance such as wildfire.

The breakout report out for the UCRB highlighted some unique IHTM capabilities. The UCRB and its relationship with the broader Colorado River represents one of the most heavily managed, modeled, and impactful basins in the world. Consequently, there is a uniquely diverse range of existing models, and the region is data rich. Multiple agencies have established regional testbeds and there are a growing number of monitoring campaigns, as well as innovations in piloting emerging observational technologies. One of the largest identified gaps is aligning incentive structures to enable participation in coordinated IHTM activities by multiple agencies (federal, states, and tribes) with different missions, as well as federal labs and university researchers. In terms of the R2O2R contributions, there is a need for better mechanisms for managers and decision-makers to be involved in evaluating and informing major modeling activities. Human systems, governance, and institutions remain poorly resolved in many modeling frameworks. The critical need is to enhance IHTM capability outcomes to give UCRB decision-makers a better understanding of the long-term growing drought risks with climate change and the allocative challenges of the basin. Better coordination mechanisms are needed for shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and improved open science protocols. An IHTM testbed should seek to develop near-term opportunities for collaborations that leverage existing major federal efforts.

3.1.4 Great Lakes Testbed

Plenary Speakers: *Rob Hetland (PNNL) and Debbie Lee (NOAA)*
Breakout Leads: *Venkatesh Merwade (Purdue University) and Rebecca Muenich (*University of Arkansas*)*
Testbed Writing Lead authors: Venkatesh Merwade (Purdue University), Rebecca Muenich (University of Arkansas), Ryan McGehee (Iowa State University), Nancy Barth (USGS), Joe Hughes (USGS), Scott Painter (ORNL)

The Great Lakes region (GLR) is a bi-national area between Canada and the U.S. around the Great Lakes, encompassing the U.S. states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin, along with the Canadian province of Ontario. The GLR constitutes the most significant accumulation of unfrozen freshwater in the western hemisphere, amounting to approximately 22,675 km^3. Besides the freshwater lakes, the GLR ecosystem includes a complex network of tributaries and groundwater on which the lakes depend, thus making this testbed's hydrology suitable for IHTM studies.

The primary source of water for most large public supplies comes directly from the lakes, but approximately 8.2 million people within the watershed rely on groundwater for their drinking water. A growing number of industrial and agricultural activities are also dependent on groundwater. As a result, the overall availability of water in GLR is declining.

Another hydrologic concern related to human activities is nutrient exports from agriculture and their impacts on downstream water quality. Nutrient exports are strongly affected by artificial drainage such as subsurface tile drains and agricultural ditches, which are challenging to represent in hydrologic models.

Changing climate is also playing a major role in affecting the hydrology of the GLR and water levels in the lakes, and as a result, the Great Lakes are experiencing record water level fluctuations. Recently, the surging water levels and extreme storms have eroded shorelines and impacted coastal infrastructure. Hydrologic intensification—larger storm events with increasing occurrence (frequency) and severity of droughts—has a poorly understood impact on nutrient exports. Finally, the Great Lakes and its processes are currently not accurately captured and represented in global climate models, which produces additional uncertainty when assessing climate impacts in this region.

The plenary talk on the GRL highlights interagency efforts between DOE and NOAA seeking to better understand coastal freshwater systems and their interactions with human systems. The DOE COMPASS-Great Lakes project is using high-resolution watershed modeling to study watershed processes impacting water quality in the lakes from agriculture as well as regional integrated models to study interactions between the lake, atmosphere, and land surface. The NOAA Great Lakes Environmental Research Laboratory (GLERL) addresses the complex human-natural systems that compose the GLR from an explicit R2O2R perspective to improve forecasts of lake and ecological processes, water quality, and climate. The speakers highlight examples of the opportunities for valuable collaborations because of their different points in the R2O2R life cycle (see *Using a Technology Readiness Map to Help Identify R2O2R Opportunities in IHTM* below).

BOX #1 – USING A TECHNOLOGY READINESS MAP TO HELP IDENTIFY R2O2R OPPORTUNITIES IN IHTM

The research-to-operations-to-research (R2O2R) cycle between the research and operational communities is foundational to IHTM aspirations. Over the course of the initial sessions, several speakers brought forward insights for enhancing R2O2R opportunities and clarified the steps needed for them to make significant IHTM advances. Notably, Debbie Lee (NOAA) highlighted how the Great Lakes Environmental Research Laboratory actively bridges the continuum from fundamental science understanding to translating applications to be operationally ready. She presented NOAA's technology readiness roadmap, with four component steps, (1) research, (2) development, (3) demonstration, and (4) deployment. Figure 3.2 builds on NOAA's technology readiness roadmap and highlights that, in practice, all these steps interact closely. The illustrated pathway provides a clear articulation of the R2O2R concept that is broadly relevant across the agencies and communities advancing IHTM. As a specific example from the plenary talks, the DOE HyperFACETS project's Storyline Approach presented by Paul Ullrich focuses on enhancing fundamental knowledge of climate events while using stakeholder engagement to clarify the value of targeted advances in fundamental knowledge in later steps in the R2O2R pathway. The roadmap also illustrates how, in the deployment phase, there tends to be one model for very specific users and applications. This was reflected in the IHTM 2.0 workshop by the diversity of highly tailored regional modeling systems presented by the different U.S. agencies. Moreover, discussions during the workshop's breakouts converged in recognizing the need to embrace the different sequences and combinations of Rs and Os to create IHTM opportunities. Flexible and adaptive R2O2R pathways are increasingly important given the growing complexity of models and modeling toolchains. In this sense, the IHTM 2.0 workshop has served a valuable role in cataloging current IHTM capabilities across readiness levels and clarifying the technical needs to share resources and knowledge across collaborators within testbeds. The R2O2R pathway illustrated in Figure 3.2 is critical to consider in the development of testbeds to make success generalizable and actionable.

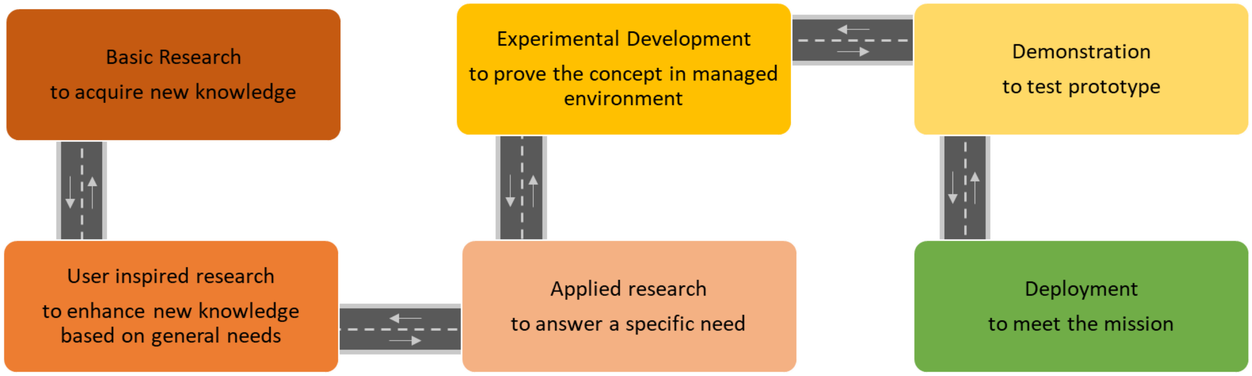

Figure 3.2. Simplified readiness level roadmap to clarify R2O2R opportunities across agencies; opportunities will highlight clear understanding of the readiness levels (source: NOAA readiness levels, adapted by N. Voisin).

The GLR captures more than 20 percent of the world's freshwater. Current IHTM efforts bridge many cooperative entities (local communities, multiple states, and Canada) and broad governing bodies (e.g., the International Joint Commission). The system has many existing models and significant data resources, such as high-resolution stream water quality data (daily, 40+ years), lake evaporation, and lake temperature, as part of a 40-year reanalysis dataset. Major identified gaps from the breakout session are the representation of major human systems (e.g., reservoirs, farmer data, etc.) and modeling frameworks capable of capturing the entire region. Integrated full regional models face data constraints, international collaboration challenges, and broader capacities to run large-scale modeling workflows (e.g., staff as well as computing). Highly valued advances in IHTM capabilities for the GLR would be improved whole region workflows to create high-resolution modeling frameworks that bridge Earth system to local scale dynamics. There is a strong potential for bridging the strengths of research agencies (e.g., computing support) and operational agencies (e.g., comprehensive monitoring datasets) to strengthen their individual as well as collective advances.

3.1.5 Mississippi/Gulf Coast Testbed

Plenary Speakers: *Lauren Schmied (Federal Emergency Management Agency [FEMA]) and John M. Johnston (EPA)*
Breakout Leads: *Jodi Ryder (USACE) and Adam Schlosser (Massachusetts Institute of Technology*)
Testbed Writing Lead authors: Jodi L Ryder (USACE), Limei Ran (USDA Natural Resources Conservation Service [NRCS]), John M Johnston (EPA Office of Research and Development [ORD]), Mukesh Kumar (University of Alabama), Yongping Yuan (EPA ORD)

The Mississippi River Basin (MRB), the largest river basin in U.S and third largest in the world, extends over 3.2 million square kilometers and overlaps 31 states and 2 Canadian provinces. With elevations ranging from 4,400 meters to sea level,[3] 10 Köppen climate types,[4] and 9 major

[3] Commission for Environmental Cooperation Working Group. 1997. *Ecological Regions of North America: Toward a Common Perspective*. Montreal: Commission for Environmental Cooperation, 71 p.

[4] Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. "Updated World Map of the Köppen-Geiger Climate Classification." Hydrology and Earth System Science 11 (5): 1633–1644.

land resource regions,[5] the MRB encompasses 6 hydrologic unit code (HUC) 2 watersheds. The MRB is an agricultural watershed, hosting 57 percent of all farmland in the U.S., and it drains 40 percent of the continental U.S.

The aquatic and terrestrial environments of the MRB are home to significant numbers of threatened and endangered species across all plant and animal categories. More than 11 million people live in major population centers along the river itself, with a total of 27 percent of the U.S. population living in the basin. Over 600 million tons of cargo are moved through the river system each year, including petroleum and petroleum products, raw and fabricated materials, manufactured goods, and agricultural products.

The MRB is the largest contributor of fresh water, nutrients, and sediments into the Gulf of Mexico. The Mississippi/Gulf Coast (MGC) testbed, including MRB and the Gulf Coast of the U.S., represents a wide range of geographic provinces and economic sectors that hold tremendous cultural and historical relevance for the U.S. The MGC also represents a wide cross-section of infrastructure for water management and flood control, transportation, energy, and recreation. Inclusion of the Gulf Coast, with contributing lands of MRB, adds an additional three states in the U.S., as well as increases the diversity of ecoregions, climate types, land resource regions, economic activities, and major infrastructure systems.

Alarmingly, the region faces significant hydrologic and water quality challenges: significant groundwater depletion and its consequent impact on streamflow and salinity intrusion (especially in the Mississippi Alluvial Plain and the coasts), nutrient runoff from agricultural activities causing recurrent algal blooms and hypoxia, sedimentation, flooding, and drought. These challenges are getting exacerbated by a combination of natural and human factors, including alterations in extreme weather regimes, aging water infrastructure, and the complex interactions between urban development, agriculture, and natural ecosystems. The Gulf Coast is also dealing with rising sea levels, saltwater intrusion, and the loss of coastal wetlands, which serve as natural barriers against storms. Overall, the region faces challenges across the agriculture-energy-water sectors with national consequences. With diversity across so many aspects, the theme of the MGC testbed can be framed as that of multiscale cross-sector interaction and management.

The plenary talk highlighted agency perspectives on IHTM advances in addressing flood risks from FEMA and USACE and Gulf hypoxia from EPA. FEMA is providing more comprehensive flood hazard and risk data by advancing the Future of Flood Risk Data (FFRD) framework which is producing probabilistic flood hazard risk data based on 2-D modeling and a statistical framework built jointly by USACE and FEMA. EPA has efforts addressing climate change and land use change (including crop management practices) effects on hypoxia in the Gulf of Mexico by advancing the Gulf Hypoxia Multimedia Modeling Framework.

The Gulf Coast/Mississippi Region is the largest U.S. river basin with intensive federal, state, local, and tribal efforts shaping its management, given its dominant impact on the national economy and global trade through support of navigation. The system has a broad array of existing IHTM capabilities addressing extremes (floods, droughts, hurricanes, sea-level rise), water quality challenges, and the complex feedbacks with the human systems it supports. One of the largest identified gaps from the breakout session is the lack of consistency in representing

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[5] United States Department of Agriculture, Natural Resources Conservation Service. 2022. *Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin*. U.S. Department of Agriculture, Agriculture Handbook 296.

the multi-sectoral demands, water requirements, and risk targets across the array of challenges facing the region. Overall data on these issues are sparse given the scale of the entire drainage area of the Mississippi River where key smaller features (e.g., wetlands) are not well resolved. This poses challenges balancing decision relevance for stakeholders, appropriate levels of model complexity, and uncertainties in model-based analyses. Highly valued advances in IHTM capabilities for the Mississippi/Gulf Coast Region would be improved infrastructure for shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and guidance on handling data confidentiality concerns that emerge across different application areas. Formal IHTM model intercomparison projects hold significant promise. There would be high value for near-real-time model maintenance, support for rapid deployment of workflow configurations, and computational support of large-scale risk assessments.

3.2 Topical (WHAT) and Methodological (HOW) Challenges of IHTM

Plenary Speakers: Ruby Leung (PNNL), Alison Appling (USGS), Nathalie Voisin (PNNL), Chris Vernon (PNNL), Roland Viger (USGS), Martyn Clark (University of Calgary), Jordan Read (CUAHSI)

The workshop was organized according to a “WHAT” and “HOW” framework, with the common underlying “WHY” being the integrated water resource challenges and the “WHO” defined through interagency and cooperating academic partners. Our “WHAT” is the thoughtful stewardship of our water resources through better-informed decision-making and the accelerated advancement of our understanding and predictive capability of the integrated water cycle, including quality, quantity, use, hydrologic extremes, and human systems. This incorporates the multiscale nature of the problem, from regional to national and over time.

Plenary talks were dedicated to focusing on major challenges in the collective “WHAT” including hydroextremes, water quality, and human systems. The processes driving hydroextremes are evolving with climate change, human activities, and vegetation dynamics and this remains a critical challenge in understanding and predicting these events. The interactions among the drivers and remaining uncertainties limit our ability to evaluate their combined influence on future states, especially in precipitation and evapotranspiration and the regulation role that vegetation plays as well as the exacerbating effects of wildfire. Additionally, a realistic representation of human systems in integrated hydro-terrestrial models is needed to achieve substantial advances. Human systems interact with the water cycle and each other across scales, through their organized and evolving water demands and uses. A current R2O2R challenge for IHTM is addressing the dual roles that human systems have as both consumers of climate services, as well as agents of changes that shape broader-scale dynamics. Finally, this plenary session emphasized the need for integration in IHTM, and suggested foci are (1) Data Resources, (2) Staff/Science Expertise, (3) Understanding the Interactive Effects of Drivers, (4) Exploring Key Feedbacks in Dynamics, and (5) Aiding Society to Better Balance Risk-Benefit Tradeoffs. The testbeds can serve as the hub for integration foci (see Science by Design – Integration as the Focus for Testbeds below).

BOX #2 – SCIENCE BY DESIGN – INTEGRATION AS THE FOCUS FOR TESTBEDS

In all national and regional cases, successful testbed design requires a clear focus from the start on developing well-defined experiments, harmonization of tools, and information exchange. The IHTM 2.0 workshop participants strongly emphasized the open science data and tools as critical attributes to make novel and substantial advances. As illustrated by Allison Appling (USGS), the key foci of designing IHTM testbeds to support integrated insights include broad access to data, sustained investments in the diverse areas of expertise needed, workflows that clarify how processes interact, broad enough questions to understand key feedbacks across human-natural systems, and decision relevance to explore key tradeoffs (Figure 3.3). These foci offer the opportunity to bridge advances in fundamental understanding, including key process interactions or feedbacks within the operational contexts that shape them, as well as societal tradeoffs across management challenges. Each of those foci can provide an explicit measure of success for the different testbed. While it might not be realistic for each testbed to advance on those foci across all R2O2R readiness levels, a strategic combination of clearly focusing on societal needs, key gaps in fundamental understanding, and advances in analysis methods would help testbeds to maximize opportunities to advance IHTM across agencies.

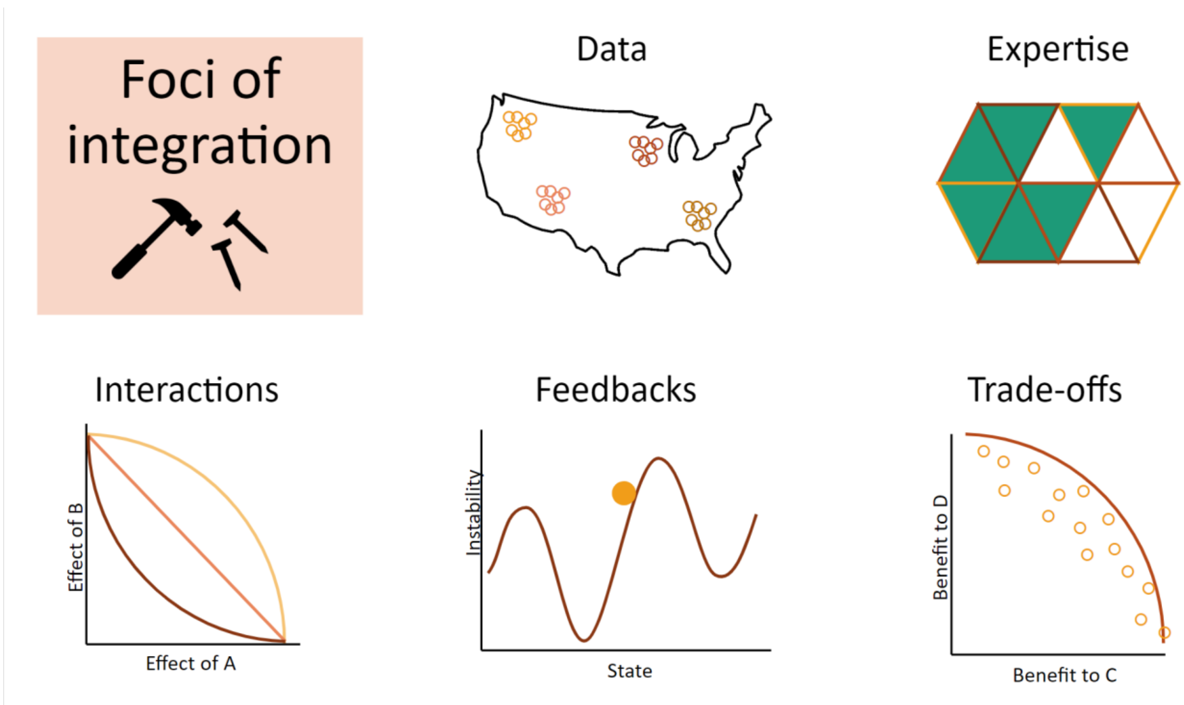

Figure 3.3. Attributes of success for test beds to realize major societal benefits (source: A. Appling).

To effectively span the space from R2O2R and the evolution of products to address changing needs, there is a critical need to be clear on both the what and the why before the how can be addressed. An example of this came from a plenary talk on the Corps Water Management System (CWMS), which is used for real-time decision support for water management and ensures consistent operation across a multitude of offices. The USACE Hydrologic Engineering Center (HEC) develops new procedures and programs that meet the changing needs of USACE, the country, and the profession and that utilize new science and technology. This is essentially bringing the "state-of-the-art" into "state-of-the-practice." The HEC platform has a wealth of free training and documentation, as well as technical assistance available online (Discourse). However, the open-source aspect is a security challenge.

Within the overarching IHTM framework, "HOW" we will do this is by better data and better models through data management, community platforms and standards, software engineering for interoperability (the ability of computer systems and software to exchange and make use of information) and sustainability, and cross-disciplinary workflows. There were plenary presentations highlighting key elements of "HOW" IHTM needs to move forward including through open science. The commitment to open science is critical to fully realize the benefits of diverse expertise, emerging insights, and accelerating the IHTM community in making major advances. Examples for open science and community building were drawn from the recent establishment of the MSD Community of Practice (CoP) supported by the DOE Earth & Environmental Systems Science Division. MSD CoP published an organizing vision for research challenges and made open science, as well as Findability, Accessibility, Interoperability, and Reusability (FAIR) principles, central to community goals.

Better models through community platforms and standards were also emphasized in the plenary presentations. Model benchmarking emerged as a critical component of community modeling that is a known gap for IHTM 2.0 currently. The setup of model applications, including pre-processing, calibration, and exploration, as well as running model applications and evaluation of model applications' results, are all dependent on transparent workflows that others can use. One example of a resource to support workflow and model benchmarking choices came from an overview of the USGS/NCAR Hydro-terrestrial Earth Systems (HyTEST) project. HyTEST focuses on using community-adopted standards, tools, and approaches, all of which are scalable by design and enable reproducibility on an infrastructure that is accessible to all. The geospatial fabric is an element of a testbed that will foster community modeling through development of a shared framework for establishing various scales and extents of model domain, alternate realizations that permit the flexibility for a variety of modeling goals and applications, the persistence of various feature identities, and interoperability (see The Shared U.S. Geospatial Fabric that Underlies IHTM below). Additionally, HyTEST is evolving the International Land Model Benchmarking (ILAMB) scorecard as an approach to guide the model evaluation process in a manner that standardizes the application of a set of statistical methods to simulated model output and observations (or other datasets held as representing "truth") to generate a result of performance for modeling applications.

BOX #3 – THE SHARED U.S. GEOSPATIAL FABRIC THAT UNDERLIES IHTM

In IHTM, the geospatial fabric is an important element of a testbed. It defines a high-resolution set of hydrologic features, such as rivers, lakes, and watersheds, that are well connected with each other and with ancillary information, such as land cover and soils information, that is used to parameterize model applications. It provides a common starting point from which the geospatial information used in modeling can be derived in systematic and repeatable ways, and which supports comparability across a diversity of hydro-terrestrial simulations designed to address different science questions, at different scales, and for different areas of interest.

A suite of web services around this core geospatial fabric supports the development, testing, and sharing of modeling workflows. Important pieces supporting these services are a rich metadata model that not only describes relevant ancillary data content but also how those data are geospatially or hydrologically located on or associated with the geospatial fabric, and a catalog for working with the metadata. Services include discovery, access, and transformation of information content. An example is determination of the dominant vegetation type for all catchments between two gages on a stream reach. This is all done in an enterprise way, at scale, requiring a robust infrastructure that includes modern software development, testing, and deployment practices that are cloud optimized.

As a specific example illustrated in Figure 3.4, the NHGF provides a common base dataset and tools for generating model application-specific spatial modeling units in a predictable way. The NHGF organizes information according to hydrology using the concept of "hydrographic addressing," and realizes web services around that concept in the form of a network-linked data index. NHGF also provides access to high-value data themes, including dynamic landscapes, river corridors, and hydrogeology, that are strategically added to the NHGF implementation. Hydrogeology is developed in collaboration with USGS National Extent Hydrogeologic Framework-to characterize the nation's hydrostratigraphy and integrate it with the more general NHGF. This includes aggregating, developing, and integrating things like a national groundwater well database, principal aquifers and secondary hydrogeological regions, and a metadata schema for groundwater models. The NHGF is also participating in the development of a community river corridor data model, including a national cross-section database. These and other artifacts, such as remote sensing-based inundation modeling (e.g., Landsat Dynamic Surface Water Extent, DSWE), and national hydrogeomorphic data, are described and accessible through the NHGF catalog.

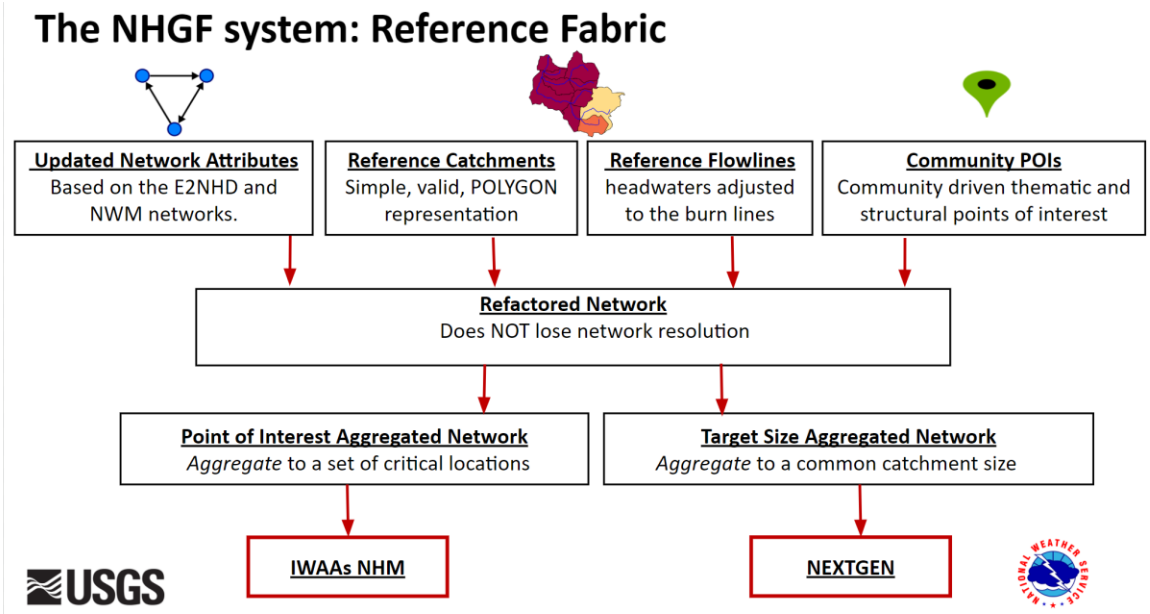

Figure 3.4. NHGF provides a common base for generating spatial modeling units (source: R. Viger).

The "WHO" of IHTM is a better community that fosters collaboration and redefines the culture of science through service leadership and open science. An interagency working group is seeking to build a community of practice (CoP; see Is IHTM Ready For a Community of Practice? below) that covers the R2O2R life cycle with partners in academia and elsewhere. Plenary talks explored the challenges and opportunities posed in establishing an interagency IHTM CoP for hydrologic modeling. The challenges that IHTM encompasses including a broad array of models, application foci, and their underlying research and operational communities highlight the need for establishing a CoP. However, the community needs to proceed with caution in thinking through the lens of a "one-size-fits-all" single model or modeling framework. An example is provided by the NOAA Office of Water Prediction NextGen water resources modeling framework. The NextGen framework seeks to run multiple models of different type and complexity across large geographical domains.

The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is focused on helping to create the ecosystem of technical infrastructure to meet water research needs and the cultural and community-focused shifts needed to advance IHTM. The community has made progress in creating open data, but this is still a challenge because there is still a need for the critical infrastructure necessary to work together. There is also a need to invest in technologists, trainers, and coordinators that engage the community, as well as to help establish new baseline skills. The community will benefit if we can celebrate and reward the diversity of professional water roles. This represents one part of a necessary change in culture in the current community that still tends to celebrate and reward more traditional disciplinary science. Other changes might include a reexamination of the reward structure that would enable both followership in using existing tools and approaches as well as leadership in new innovations to foster building a community set of tools.

BOX #4 – IS IHTM READY FOR A COMMUNITY OF PRACTICE?

The IHTM 2.0 workshop provided an exciting forum for federal agency representatives and the research community to discuss opportunities to accelerate advances in fundamental knowledge, broaden community-level investments in testbeds, and better address the nation's water challenges through R2O2R pathways. Across the different presentations and breakout discussions, key motivations for developing a formal IHTM CoP were well articulated (e.g., the discussions by Martyn Clark and Jordan Read). Strong thematic focal points emerged throughout the IHTM 2.0 workshop related to shared data requirements where there is significant complementarity for developing the community data frameworks, growing open science motivations to share codes and workflows to accelerate advances with a more efficient use of resources, and the shared vision of needing better model benchmarking frameworks for meeting our nation's needs. Importantly, any IHTM CoP needs to leverage and amplify existing CoPs.

Jordan Read presented on CUAHSI, a consortium of universities supported by NSF to support FAIR science and promote collaboration in water science, water resources management, and water resource protection and enhancement. CUAHSI is playing an important role in addressing community data sharing systems and training opportunities. The CUAHSI community, however, would benefit, as Read mentioned, from more institutional coordination and opportunities to train the new technical generation across the shared resources of the U.S. federal IHTM enterprise. Other CoPs like Community Surface Dynamics Modeling System (CSDMS) were also mentioned during the workshop. CSDMS offers complementary synergies, where the community's Hydrology focus research group is sponsored by CUAHSI, and the human dimension focus research group provides another entry point for IHTM's focus on better representing human systems.

A clear value of and need for an IHTM CoP includes improved inter-institutional coordination and enabling a richer suite of R2O2R pathways to be realized. For example, current efforts addressing pressing needs from the nation, for example the U.S. National Climate Assessments to date and the ongoing first National Nature Assessment, are limited due to a lack of consistency across use-inspired research datasets and modeling resources.

Should IHTM establish a distinct community or be a subset of an existing CoP? This important question remains open. In whichever form, the IHTM CoP would contribute to existing communities and would also help to better address the pressing needs of the nation.

The topical themes, methodological challenges, the common underlying challenge of integrated hydro-terrestrial modeling, and a burgeoning IHTM CoP all ultimately integrate to build place-based testbeds to improve our ability to provide water scenarios to our stakeholders and the public. The testbeds also lead back out in an iterative process to inform our “WHO,” “WHAT,” “WHY,” and “HOW.”

4.0 Aspirational Visions for IHTM Testbeds

The plenary presentations summarized in Section 3.0 synthesize where we currently are with respect to progress on regional and national testbeds and provide a comprehensive, though not exhaustive, inventory of the capabilities, challenges, and needs. They draw on interactive discussion sessions that further capture the insights and experiences of all IHTM participants. These sessions were faithfully recorded in a set of artifacts: extensive free-form notetaking by external ORISE (Oak Ridge Institute for Science and Education) writers, documents to capture individual responses used to generate collaborative discussion in the session and slides to report out in a plenary. For Section 4.0, a writing team of workshop breakout session leaders were asked to contribute the content, based on their synthesis for each of the testbeds' breakout sessions, guided by prompts common to all testbeds to provide consistency. Appendix B is the outcome of the writing teams efforts including aspirational visions for how the national and regional testbeds could provide actionable advances for IHTM.

Across the testbeds, several shared, collective capabilities, gaps, and needs have emerged. The existing capabilities include models, datasets, shared scientific knowledge and understanding, existing expertise that resides in the workforce focused on IHTM, and the existing dedicated resources of their time and effort, as well as standing computing resources that can be shared among agencies and partners. Although each testbed has unique water resource challenges, common areas for modeling advancement across the testbeds include: 1) advancing understanding and integrated prediction of all elements of the water cycle, including hydro extremes, 2) incorporation and integration of human sectors into predictions of water availability, and 3) advancing understanding and prediction of water quality broadly (with specific examples given in regional testbeds).

Although progress has been made and recent advances in existing capabilities encompass the burgeoning core of IHTM in the U.S., much more can be done. The IHTM 2.0 workshop has highlighted a diverse suite of scientific, technological, and workforce challenges that can only be overcome through prioritizing IHTM as shared capability. Some of the key challenges that have emerged across the testbeds include the following:

- Improving data availability, accessibility, and accuracy
- Improved harmonization, common data and metrics standards, and shared maintenance of both existing and developed datasets at various testbed scales, improving the accuracy of prediction through the continued advancement of the integrated hydrologic sciences and incorporating extreme events
- Integrating human behavior and systems into Earth and atmospheric system processes, models, and understanding
- Encompassing multiple temporal and spatial scales
- Addressing process gaps and incorporating advances in AI/ML.

To address these shared challenges, some common needs have been identified across the testbeds. Cloud-hosting solutions have accelerated the ability to host and share common datasets and forcings, but there is still a need to bolster the shared resources and allow equitable access for cyberinfrastructure and data storage that implements the leading-edge best practices for both R&D and operational modeling. The IHTM endeavor would greatly benefit from dedicated staff time encompassing the various fields of expertise needed to build and maintain a robust, IHTM CoP, including ongoing technical support. Identifying the responsible agencies for hosting the CoP (and, therefore, willing to commit resources for staff time) is critical. Resources are needed to provide training in existing and emerging IHTM capabilities and early career pathways to encourage a diverse workforce to develop their skills in modeling and associated cyberinfrastructure. A common understanding of the R2O2R life cycle that is driving agency development and needs and a shared governance guiding community engagement is needed. It will be helpful to continue to learn from R2O2R success stories across the agencies at both regional and national scales. Finally, we need to eliminate barriers to funding and create innovative funding mechanisms that can sustain research through the various phases across the complete R2O2R cycle, including multi-year timelines, planned rollover between Technical Readiness Levels (TRLs), increased funding for communication and tech transfer activities, and scheduled transitions between R&D and operational funding sources.

The emerging vision of a nascent IHTM is generally consistent across the testbeds. The current community is seeking a common and maintained platform and digital hub for model documentation and benchmarking, data and knowledge sharing, open workflows, model applications, and codes. This common platform also includes searchable data and model catalogs, as well-established standards for data, models, interfaces, and geospatial fabrics. The new IHTM workstream of USGCRP is currently developing a vision for such a community portal.

There is an acknowledged desire to enhance the inclusion of social science and a deeper understanding of stakeholder needs through the creation of co-developed scenarios and storylines. Central to the emerging vision for IHTM is regular and sustained communication through a CoP with an associated interagency working group that includes regular meetings and asynchronous information exchange through the hub. The USGCRP has started a new IHTM workstream in March 2024 that represents the kernel of this larger CoP.

Finally, we need to enhance the accessibility of the IHTM outcomes through user-interfaces that enable broad community engagement and participation, as well as public-facing products that communicate these outcomes to decision-makers, stakeholders, and the broader public.

5.0 Key Next Steps and the IHTM Roadmap

The IHTM 2.0 workshop provided valuable insights for advancing sustainable and efficient development, operation, and maintenance of nationally consistent water prediction and projection capabilities. Sections 3.0 and 4.0 of this report (and the associated Appendix A and Appendix B) clarify the opportunities and further requirements for interagency coordination, the effective use of resources, and approaches for incorporating community research advances. IHTM offers a platform that could ideally support the various operational and educational needs of the water mission federal agencies, yield solutions to water-related problems at multiple scales and accelerate science in service to the nation. There are both considerable challenges and opportunities associated with building this IHTM community, but the urgent need to make scientifically informed decisions about the nation's water resources mandates that we continue to advance this effort as rapidly and effectively as possible.

Section 3.0 (and Appendix A) of this IHTM 2.0 workshop report highlights a broad array of IHTM capabilities that have emerged since the first workshop in 2019, identifies critical research gaps that still exist, and provides perspectives on how to address those gaps. A key facet of this second workshop has been to contribute visions for how cooperative testbeds can accelerate innovations into societally relevant applications and facilitate sustained interagency engagements to inform and strengthen bridges between the research and operational communities (R2O2R).

In Section 4.0 (and Appendix B) of this report, the emerging common needs that stem from the visions presented for the 5 testbeds encompassing the U.S. National scale and 4 major regions (the Mid-Atlantic, Upper Colorado River, the Great Lakes, and Gulf Coast/Mississippi) provide specific spatial domains for research and operational problems that can be grounded in stakeholder priorities and leverage existing agencies' investments in IHTM capabilities. The visions for the testbeds show their strong commonalities in needs (e.g., sharing data, benchmarking models, and transparency of workflows) as well as the importance of acknowledging their key differences that emerge from the regionally diverse challenges confronting U.S. water resources systems. Overall, the central challenge that emerged across all the sessions in the IHTM 2.0 workshop is how best to establish a flourishing community of practice.

What Does IHTM Success Look Like?

A thriving IHTM community of practice can take many shapes but requires some foundational elements to succeed. As identified in many of the plenary talks and breakouts, the community seeks to establish, maintain, and regularly communicate evolving standards and requirements for data, models, codes, and their associated use and interoperability. Additionally, fostering the ability for open and transparent model intercomparison and benchmarking based on community-developed and agreed-upon standards and metrics has emerged as a recurring necessity of such a community. Enabling effective sharing of data, code, workflows, and knowledge is a core requirement of this community. The creation, integration, and communication of knowledge is clear, consistent, and reliable and continues to enhance public trust in federal and academic science. The community is inherently motivated for the public good and the advancement of water science.

When the Earth science modeling community collectively recognizes that there is great value in sharing code, workflows, and concepts across different modeling communities, an IHTM community of practice becomes tenable. Focus needs to shift from individual models to modeling frameworks, their respective communities, and the various people that are needed to support them. The bottleneck for accelerating IHTM is not solely technical or scientific, but also social. A critical limit exists at the community level for reproducibility of models, data, and workflows. An IHTM community of practice organized around a community portal as the central product and meeting place would begin to address these critical problems. The community of practice would contribute and leverage the resources provided by other relevant communities of practice, which may have different charters yet synergistic or complementary scopes.

The IHTM community of practice should establish a charter and stakeholder roadmap that use the existing testbeds and establish new critical geographic areas of opportunity and focus. The community of practice should adopt in its charter a code of conduct that fosters the core principles of diversity, equity, inclusion, and accessibility. An IHTM community of practice that addresses critical problems in integrated modeling at regional and national scales (testbeds) needs strong support and leadership from agencies while enabling open participation from all community members. These efforts should establish regular rhythms and channels of communication, such as quarterly meetings, building on existing organizational or professional meetings, and community-level updates on a dedicated IHTM community web page.

Toward this vision of success and building on testbeds discussions, below are syntheses of near- and medium-term opportunities. Building on IHTM 1.0, we conclude with the IHTM 2.0 roadmap and an associated call for action.

5.1 Near-term Opportunities

In the next 1–3 years, the opportunities for IHTM should continue to advance under the stewardship of the USGCRP and its leading agencies (and any other government agencies or academic partners that wish to participate). Following the IHTM 2.0 workshop in March 2024, USGCRP launched an IHTM interagency workstream that consolidates subsets of the Integrated Water Cycle Group and Coasts Interagency Group memberships, along with interested federal participants of the IHTM 2.0 workshop to sustain engagements across agencies and enhance the momentum. The workstream meets monthly and is open to all federal employees and affiliates. A major focus of the workstream has been to establish an initial version of the IHTM Community Portal, ihtmcommunity.org, as a hub for building a potential community of practice that is oriented around testbeds and technical capabilities. The workstream highlights work within and across agencies that can potentially contribute to and benefit from an IHTM community of practice.

5.1.1 Leveraging Scientific Meetings for Community Building

Another near-term opportunity to build on the momentum of IHTM 2.0 is to use existing scientific organization meetings such as WaterSciCon in 2024, the 2024 AGU Fall Meeting, and other local and regional meetings that could enable: (1) communication of the current status of the community and its priority directions and needs through technical presentations, (2) collaboration through jointly submitted abstracts, presentations, and posters to drive advancement within testbeds and areas of foci and integration, (3) fostering community mindset through sustained connection and social gathering, (4) building the community through networking and connection to students and colleagues. As examples of early success on those near-term opportunities, workstream members organized IHTM technical sessions with academic collaborators at two national meetings (WaterSciCon24 in St. Paul, MN, and the Fall 2024 AGU Meeting in Washington, DC). At the WaterSciCon24 meeting, leaders of the IHTM Workshop and the USGCRP Workstream organized a half-day workshop to share with over 60 participants the IHTM 2.0 workshop findings and to design within breakout groups IHTM computational experiments at regional and national scales that could both benefit from and contribute to an IHTM community capability. The response from the workshop participants and the group exercise validated the potential impact a thriving IHTM community of practice could have within the water resources community.

5.1.2 Collaborative Modeling Efforts and Resource Sharing

The IHTM community is certainly not starting from scratch. In the near term, the community can leverage several major CONUS-scale modeling efforts and try to move toward the adoption of common standards for the formulation, execution, and evaluation of those national-scale modeling applications. This is currently happening as part of the planning efforts by the DOE, USGS, and USBR for the next round of SECURE Water Act Assessments and by the USACE and USBR in support of generating CMIP6 CONUS-wide hydrologic projections. The National Center for Atmospheric Research (NCAR) is currently funded by the USACE and the USBR to produce reliable, consistently generated, CONUS-wide CMIP6 hydrologic projections. As the H2US academic-led effort advances, it could adopt some of the standards and common elements proposed for use in the SECURE Water Act Assessments and being applied by NCAR in support of developing and evaluating the reliability of the CONUS-wide climate-influenced hydrology product. The outputs of these national-scale applications should be intentionally and consistently curated and made easily available to the broader community, leveraging open science principles and practices. Other agencies and groups can also join in and benefit from this effort to adopt standard elements and approaches in the development and execution of their national-scale modeling efforts.

In addition to those national-scale hydrological applications, the USGS, for example, is also performing regional-scale assessments in the following five Integrated Water Science (IWS) Basins: the Delaware River Basin, the Upper Colorado River Basin, the Illinois River Basin, the Willamette River Basin in Oregon, and the Trinity-San Jacinto River Basin in Texas. Each of these five regional assessments starts with output from the national-scale models and is then redefined, as needed, using shared protocols, workflows, and tools. The goal is to build a multiscale modeling capability that can be used to support assessments anywhere within the United States. The SECURE Water Act Assessments conducted by the DOE and USBR also conduct regional-scale assessments, which leverage the national-scale modeling applications. The output of these assessments, as well as the models, datasets, and workflows used to produce the assessments, can be shared with the broader community as initial IHTM products through the IHTM Community Portal in support of establishing a thriving IHTM Community of Practice.

Many other agencies support similar types of work that could be shared through the IHTM Community Portal. For instance, DOE's Earth and Environmental Systems Modeling program is building highly interoperable modeling frameworks that integrate hydrology within complex, interacting, human and natural landscapes in regional test beds through the Integrated Coastal Modeling (ICOM) project, the Great Lakes Modeling (COMPASS-GLM) project, and the Interdisciplinary Research for Arctic Coastal Environments (InteRFACE) project. The modeling frameworks have been built to facilitate cooperation and collaboration with other modeling teams and groups. These and many other IHTM-related projects can be found at https://climatemodeling.science.energy.gov/projects. Finally, DOE and USGS are in discussions and early planning of computational testbed opportunities in Philadelphia, PA, and Sonoma County, CA, contrasting East and West Coast systems and dynamics.

5.1.3 Opportunities to Leverage Funding

Although there are ample opportunities for collaborative modeling, knowledge sharing, and building an IHTM CoP, explicit funding for IHTM development is currently not incorporated into an existing congressional mandate or agency funding priority, nor is it part of any one single agency's mission. As such, its near-term success should not be reliant on specific agencies, existing priorities, or new funding streams. This does not preclude its advancement through open opportunities for collaborative integrated science and modeling.

One example of such opportunities is the USGS John Wesley Powell Center for Synthesis and Analysis, an initiative that aims to foster innovative thinking in Earth system science through collaborative analysis and synthesis of existing data and information. Water resources are one area of focus, and previous proposals have included hydrologic forecasting. The Community for Data Integration (CDI) is a dynamic community of practice working together to grow USGS knowledge and capacity in scientific data and information management and integration. CDI also has proposal-driven funding opportunities that could be relevant to IHTM needs.

The National Science Foundation (NSF) has several programs that support research on natural and anthropogenic drivers of water quality, hydrologic extremes, and water quantity across a broad range of spatial and temporal scales. NSF also has a broad spectrum of programs that support observational infrastructure, cyberinfrastructure (Figure 5.1), and workforce development that span Earth Sciences, the Geosciences more broadly, and the interfaces of these fields with other domains of science and engineering across NSF. Members of the research community can submit proposals on IHTM-related concepts to programs closely aligned with the team's primary objectives.

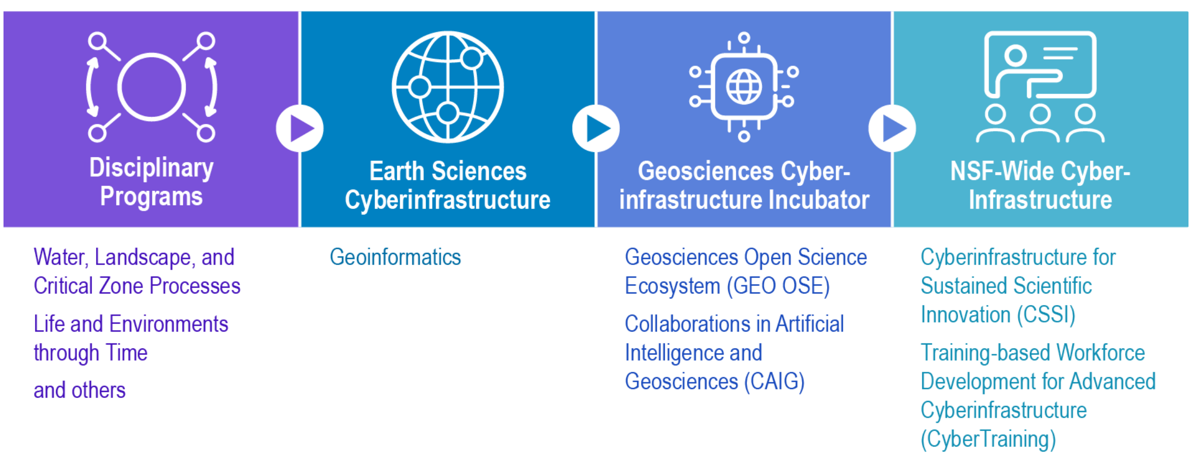

Figure 5.1. Examples of programs at the National Science Foundation, as of December 2024, that support research and cyberinfrastructure development with Earth Sciences, the Geosciences Directorate, and across the Foundation.

Using these opportunities effectively could involve collaborative proposals that include both agency and academic partners. These proposals, based on both existing and emerging testbeds, could address community-identified gaps such as the development of model evaluation metrics and scorecards or evaluation of various storylines or scenarios for water availability.

Overall, it is important to look for opportunities to align and coalesce existing IHTM modeling efforts performed by different agencies and university investigators by encouraging the adoption of common standards and approaches for experimental design and evaluation and the public sharing of the results, including modeling codes, datasets, and workflows while adhering to open-science principles that promote reproducibility and extensibility of the modeling work. Science funding agencies could encourage the development of proposals that adhere to the IHTM principles, leverage existing community assets and resources, and contribute to advancing IHTM capabilities. Proposals that bring together existing assets from multiple agencies and organizations in synthesis activities could be especially encouraged, as these relatively modest efforts would build upon existing capabilities to help establish an IHTM Community of Practice. Additional community assets that could be leveraged in this way include CUAHSI, CSDMS, and the MSD Community of Practice.

It is critical, at this stage of community development, to capitalize on momentum and continue to build confidence in our success. As the community grows and evolves, requirements for sharing and reporting outcomes (and potential governance associated with these activities) will also grow and evolve as needed.

5.2 Medium-term Actions

A thriving IHTM community that works collectively toward creating a shared capability is currently within our reach, and the near-term path forward can build on existing momentum. However, at the 3–5 year medium-term planning horizon, there are still significant organizational, cultural, financial, and technical obstacles to overcome to achieve and maintain this vision over the long term. Sustained funding and commitment from federal agencies and academic partners will be needed to grow and maintain the community for the long term. Where feasible, the shared priorities and known gaps, as well as existing activities in the testbeds, should drive possible shared budget initiatives or new shared funding programs. Participating agencies could identify existing funding mechanisms that may have the flexibility to enhance existing efforts and pilot new collaborations, as well as develop and enhance the infrastructure that can foster an open community. Essential to this is funding for the communication and curation of reusable assets. Agencies and partners could develop stable mechanisms to provide support for community of practice leads and facilitators in addition to providing community training. Since IHTM 1.0, significant progress has been made in determining data and model standards, continuing these efforts, including promoting these standards and best practices through outreach and training, will help provide efficiencies and synthesis among federal partners.

Cultural change may arguably be our biggest challenge, as plenary presentations and breakout discussions demonstrated. In the next 3–5 years, medium-term actions that could fuel culture change include the establishment of a governance strategy to manage IHTM in a more formal way as well as formalizing interagency relationships. An important element of this governance should include a process that communicates how communities of practice operate, as well as a community model benchmarking process. A large challenge that remains is changing the incentive structure. The current incentive structure is still largely based on individual recognition and achievement for novel (and mostly incremental) innovation even though Federal science (and, to a degree, academic science funded by federal agencies) is intended for the public good and service. This requires continuing to incentivize team science and redefining what innovation looks like. Reusing existing community tools and capabilities and the importance of “leading through following” were identified as significant culture change needs. This should be adopted wherever possible by the scientific community at large, such as science and professional associations, in consideration of awards and recognition. The public will benefit from consistent and coherent water science that it can trust and rely on; this trustworthy science can arise from an IHTM community that communicates internally, with outside groups, and with higher levels of government with a consistent message and voice.

5.3 IHTM 2.0 Roadmap

The IHTM 1.0 workshop report identified shared motivations that are still highly relevant to moving the community forward. Informing solutions to the nation's critical hydro-terrestrial challenges was identified as the first shared motivation. IHTM 1.0 priority challenges (HABs, Western Water Challenges, and water-related hazards) are still very much aligned with IHTM 2.0. Updated water challenges are the regional diversity of major hydro-terrestrial extremes (floods, droughts, wildfires, etc.), as well as the underlying processes that are evolving with climate change, human activities, and vegetation dynamics. Although the IHTM 2.0 workshop was not driven directly by top-down priority water challenges like in IHTM 1.0, the grassroots identification of those challenges is remarkably consistent across agencies and academia.

Major benefits of community integration identified from IHTM 1.0 are to leverage existing resources more effectively and amplify cross-agency impacts. Four years later, community integration has become even more critical. The nation needs trusted understanding and prediction of water resources under rapidly changing climate and land use conditions. Strengthening R2O2R connections and accelerating the timeframe between scientific and technological innovations to societal benefit was identified as another shared motivation that has been amplified during the IHTM 2.0 workshop. It is essential for society that the R2O2R life cycle be better connected and integrated across IHTM community contributions for water resources to be managed effectively now and into the future. Finally, overcoming technical and institutional barriers remains as important now as it was in 2019.

The following are priority near-term action items from IHTM 1.0 in 2019 that bear noting from the resonant themes that emerged from IHTM 2.0.

- Establish a community of practice oriented around technical working groups, shared capabilities, and improved communications and coordination.
- Organize joint community workshops and webinars, including IHTM user training events.
- Determine and implement common data and model standards with the goal of developing a mature, formalized, and standardized process for data management and interoperable code development.
- Establish a vision or charter immediately for the collaborating communities supported by agencies; develop a 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, scientific and professional associations, etc.).
- Establish agency and academic 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.
- Establish governance for IHTM community development and engagement.
- Produce a roadmap for a IHTM community of practice including pathways for adoption by various agencies.
- Define what each agency needs from IHTM and how agencies would use the envisioned capabilities to advance their missions. From these analyses, agencies can contribute to the development of IHTM design requirements.
- Formally catalog existing capabilities (enterprise datasets, models, workflows, testbeds, etc.).

The path forward outlined at the end of the IHTM 1.0 workshop was very optimistic, largely because there was a perceived mandate from the highest levels of the participating organizations and the federal Water Subcabinet. Although progress has been made, a great deal of the roadmap outlined in IHTM 1.0 did not manifest. The combination of the lack of official mandate, the lack of funding, and the COVID pandemic slowed progress. It should be noted that several participating agencies did make great progress internally on the adoption of common data and model standards. Additionally, several agencies formed smaller partnerships or paired efforts that were based on the philosophy of IHTM, using FAIR data standards and practices. These efforts were critical to make IHTM 2.0 possible and provide opportunities to advance on the roadmap.

The same drive for integrated advances in federal and academic IHTM capabilities as a collective for the public good is present in IHTM 2.0. However, the lesson learned from IHTM 1.0 is to keep goals tractable, focused, and not reliant on the addition of new funds. As a result, the IHTM 2.0 roadmap is more modest, focusing on near- and medium-term activities that will drive the community forward (Figure 5.2).

- Continue to highlight and elevate community modeling activities at science/professional organization meetings and other opportunities.
  - American Geological Union Fall Meetings
  - AGU-CUAHSI WaterSciCon
  - Environmental Prediction Summit
  - American Meteorological Association Annual Meetings
- Continue to organize joint workshops and webinars whenever possible.
- Establish the IHTM community portal, www.ihtmcommunity.org, as a hub for building a potential community of practice-oriented around testbeds and technical capabilities (Fall 2024)
  - Use the portal to communicate key developments, workflows, advancements, etc.
  - Use the portal to catalog existing capabilities through web links, etc.

- Execute computational experiments in the national testbed and a few key regional testbeds, where existing activity enables this to advance relatively seamlessly within existing budget constraints.
  - USGS, DOE, and USBR coordination of national scale modeling efforts in support of the SECURE Water Act (reports due 2030)
    - Construct computational experiments that allow for the evaluation of various atmospheric forcing datasets as well as national hydrological models.
    - Implement open-science best practices (e.g., FAIR principles) to ensure that the results of the national scale modeling efforts are openly and readily available. This will require forethought about the curation, documentation, and delivery of not just the model outputs, but also the codes, workflows, and underlying datasets used in the design and execution of the modeling experiments.
    - The national-scale SECURE Water Act assessments conducted by the USGS, DOE, and USBR are augmented by regional-scale applications in selected basins. The frameworks, tools, and datasets developed for these multiscale applications can potentially be leveraged to support additional regional-scale testbed experiments.
  - Explore the possibility of regional-scale testbed experiments through ongoing project work.
    - Mid-Atlantic Region, Upper Colorado River Basin, Great Lakes, Mississippi/Gulf Coast, as well as other areas of federal investment, including the Illinois River Basin, Willamette River Basin, and the Trinity-San Jacinto River Basin.
    - Enable computational experiments with output from national models that can be refined using shared workflows and tools.
    - Utilize both regional and national efforts to continue to advance AI/ML approaches.
- Organize efforts around areas of significant federal investment, such as enterprise datasets or models.
  - USGS and NCAR produced CONUS404, which would benefit from expanded interagency focus and evaluation.
  - The National Hydrogeospatial Fabric developed by USGS and advanced through NOAA collaborative efforts is a key federal asset that is based on community data standards.
  - Continue to advance and develop data and model standards, including data standards for AI/ML advancement.
- Continue to reflect on the value, need, and impact for IHTM. A possible outcome for IHTM computational experiments at the regional and national level would be to inform future National Climate Assessments by 2028. Other possible outcomes include multi-agency-based estimates to inform robust policymaking such as environmental regulation, infrastructure planning standards, and multi-agency coordination for preparedness and recovery to extreme climate events and development of adaptation strategies.

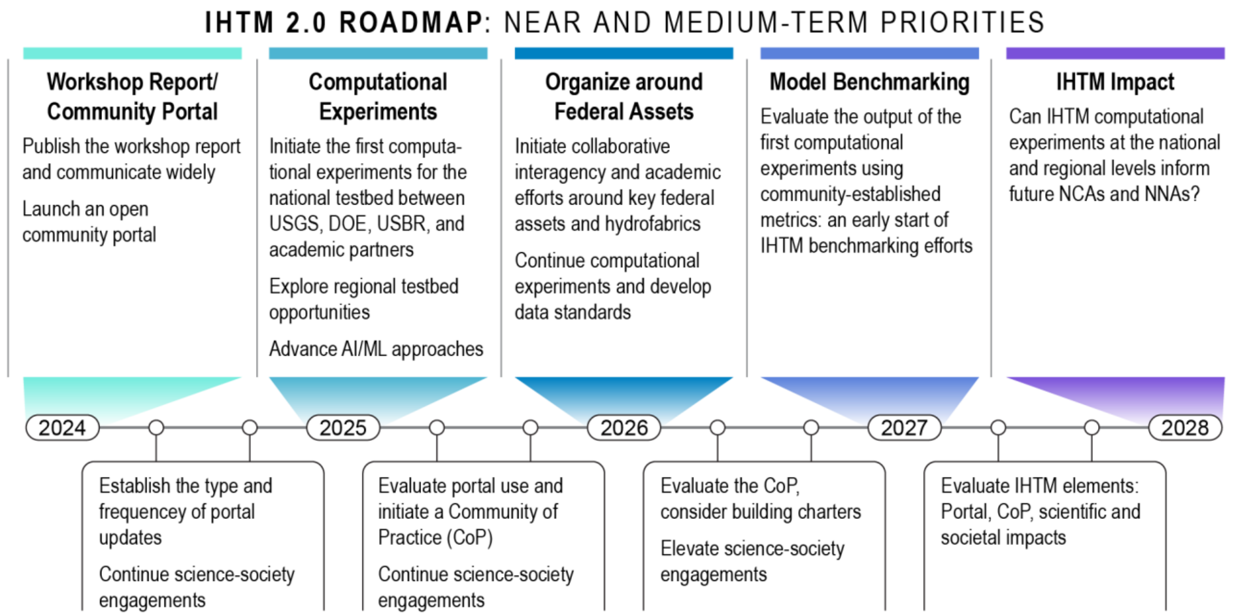

Figure 5.2. IHTM 2.0 Roadmap starting in 2024 with the release of the IHTM 2.0 workshop report. High-level interagency priority activities are shown on the top line by year, including computational experiments, organizing around federal assets, model benchmarking, and a possible contribution to future National Climate Assessments (NCAs) through existing computational experiment outputs by 2028. Ongoing maintenance activities are shown on the bottom line, including the establishment of the portal style and rhythm, engagement with scientific societies, initiation of the technical CoP, and an evaluation of all IHTM elements before a proposed workshop in 2028.

Appendix A – Plenary Discussions

A.1 National and Regional IHTM Testbed Perspectives

A.1.1 U.S. National

Sessions B and C Tuesday (10/31/2023) National Testbed – Capabilities, Gaps, and Needs
Session B Speakers: Paul Ullrich (Lawrence Livermore National Laboratory), Jacob LaFontaine (USGS), and Brenda Rashleigh (EPA)
Session C Breakout Leads: Laura Condon (University of Arizona) and Aubrey Dugger (National Center for Atmospheric Research [NCAR])

Paul Ullrich—From the Top: Atmospheric Forcing Data for Integrated Hydro-Terrestrial Modeling

This plenary talk highlighted that, at the national scale, a key integrating concern for IHTM 2.0 should be the climate time series inputs. Broadly, input climate series are available over many possible time periods: historical, pre-industrial, near-future, or far-future. It is noted that historical conditions, while important, represent only one instance of many possible dynamic sequences that could have occurred given the complex and uncertain nature of the climate system. Consequently, a single historical climate time series does not account for the internal variability of forcing and extremes. Global climate models have an important role in better exploring historical and future climate conditions (e.g., single model large ensemble runs for internal variability or multi-model projections of climate changes). Bridging these global projections to IHTM modeling at regional to local scales requires carefully considering downscaling frameworks.

Common frameworks include statistically downscaled products based on empirical or algorithmically derived relationships, dynamically downscaled products produced by regional climate models, regionally refined models exploiting nested or refined grids, and thermodynamic global warming where historical reanalysis data are modified to account for global warming.

The talk highlights that many new climate data products have emerged for the national CONUS scale and that at present it poses a significant challenge to guide users toward which is most appropriate to use (Table A.1). The need for common evaluation standards and better guidance for climate data product use is presented as a grand challenge for IHTM. Addressing this grand challenge requires connecting the climate data with user needs (salient to local stakeholders and credibly benchmarked in quality). Example strategies for improving stakeholder relevance of climate inputs (see Using a Technology Readiness Map to Help Identify R2O2R Opportunities in IHTM in Section 3.0 below), drawn from the DOE HyperFACETS project, include hindcasts of important historical events with reanalysis data, storylines where hindcasts are augmented to account for the effects of thermodynamic global warming, and downscaled synthetic events drawn from climate models.

Data coordination is highlighted as a major challenge, with ongoing efforts seeking to address it such as the Observations for Model Intercomparison Project, Earth System Grid Federation, and Multisector Dynamics (MSD) Living Intuitive Value-adding Environment (LIVE). Three types of bottlenecks are noted as ongoing concerns: technical (data formats, units, metadata), physical (large dataset sharing or subsetting), and human (public sharing of work). A noted key need for IHTM forcing data is the potential to develop a central catalog of climate data, an archive of past scenarios, data sorted and tagged by application sectors, expert guidance on using the data, and standardized evaluation of the data products.

Table A.1. New climate data products over CONUS (source: P. Ullrich, access or information compiled by I. Herold).

Statistically Downscaled Products	Grid Spacing	Years	Access or Information
Localized Analogues v2 (LOCA2)	6km / 3 km Calif.	1950–2100 (multiple)	LOCA2
Seasonal Trends and Analysis of Residuals (STAR) – Empirical-Statistical Downscaling Model (ESDM)	4 km	1950–2100 (multiple)	Hayhoe et al. 2023 Ullrich 2023
Multivariate Adapted Constructed Analogues (MACA)	12 km	1950–2100 (multiple)	MACA
Dynamically Downscaled Products	**Grid Spacing**	**Years**	
Argonne Dynamically Downscaled Archive (ADDA)	12 km and 4 km	30 hist + 30 future (x3 models)	ADDA
IM3/HyperFACETS TGW Ensemble	12 km	40 hist + 80 future (x4 scenarios)	Jones et al. 2022
PNNL Western U.S. Product	6 km	42 hist + 30 PGW (x5 ensemble)	Wigmosta et al. 2022
Western U.S. Dynamically Downscaled Dataset	9 km and 3 km	40 hist + 85 SP370 (x9 ensemble)	Rahimi et al. 2024
NCAR CONUS1 Product	4 km	13 hist + 13 RCP8.5	CONUS1
NCAR CONUS2 Product	4 km	21 hist + 21 RCP8.5	CONUS II
NCAR CONUS404 Product	4 km	42 hist + 44 SSP370	CONUS404

Jacob LaFontaine—National Testbed Capabilities, Gaps, and Needs

This plenary talk provided a detailed introduction for the national-scale IHTM-relevant USGS efforts mandated by the SECURE Water Act. The agency is mandated to (1) assess the water resources of the U.S., (2) assist in determination of the quantity of water available for beneficial uses, (3) assist in the determination of the quality of water resources for the U.S., (4) identify long-term trends in water availability, (5) use the trends to better understand how water availability may change in the future in the U.S., and (6) develop a basis for an improved ability to forecast water availability for future economic, energy production, and environmental uses.

The USGS is developing and evaluating nationally consistent indicators to reflect the status and trend of water availability, maintaining a national database of water availability data, and developing predictive modeling tools. The talk emphasized the importance of broadly addressing the supply (water quantity and quality) and demand (water use and aquatic ecosystem health) in water availability assessments (Figure A.1).

The National Water Information System Modernization is facilitating, at the national scale, more rapid and accessible data delivery to support the predictions of water hazards and availability in near real time. It includes decision support tools that aid in managing water supplies, flooding, drought, inundation, debris flow, water quality degradation, and other water-related hazards. It provides a national-scale portfolio of water web applications.

The Next-Generation Water Observing System draws on state-of-the-art measurements and dense arrays of sensors at selected sites, increases spatial and temporal coverage in key datasets, facilitates the incorporation of new technology testing and implementation, focuses on enhancing operational efficiency, and modernizes timely data storage and delivery services.

The National Water Census provides a collection of datasets on modeled water supply, demand, and availability across the U.S. It provides a model-based output complementary to the National Water Information System, including visualization and output access. The USGS is also actively advancing national modeling applications for water quantity and quality building on a variety of quantitative frameworks (e.g., physical process-based models, statistically based models, machine learning (ML), and process guided deep learning). The modeling efforts are being supported by significant coordination in the development of forcing datasets (e.g., CONUS404), geospatial modeling, and key CONUS-scale model development strategies (parameterization, calibration, and evaluation). The talk emphasizes that IHTM 2.0 collaborative opportunities reside in shared computing environments, data management/processing capabilities, formulation of shared scenarios/forcings, geospatial representation, process representation, and R2O2R governance.

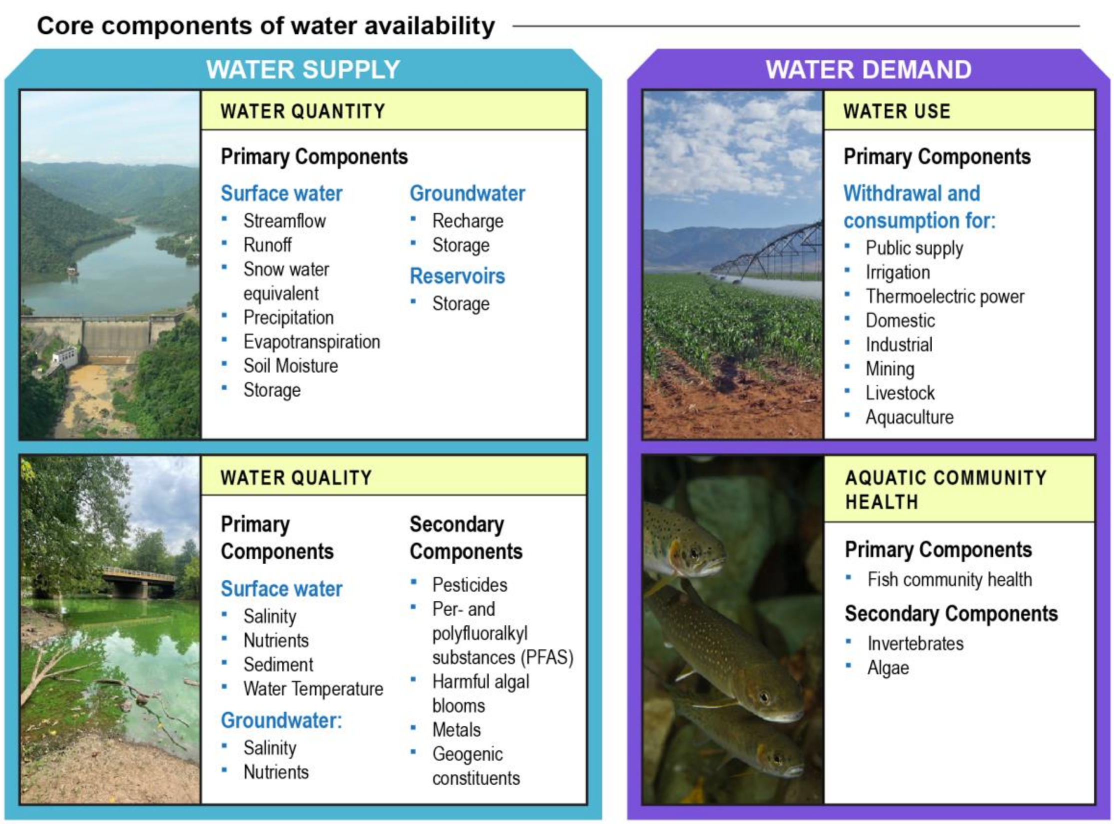

Figure A.1. Core components of water availability in the USGS Water Resources Mission Area (source: Adapted by J. Lafontaine, Design – Nathan Johnson).

Brenda Rashleigh—Water Modeling at U.S. Environmental Protection Agency

This plenary talk addressed the unique EPA IHTM needs and capabilities in addressing the agency's mission of protecting human health and the environment. Examples are provided for EPA's watershed and water body modeling efforts. In terms of agency needs, the EPA has major program drivers in the Clean Water Act (e.g., water quality standards/criteria, nonpoint source program, effluent guidelines, discharge permitting, aquatic life guidelines, and national estuary programs), the Safe Drinking Water Act, the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act, and regional programs to meet state and tribal needs. The agency uses models to assess evolving water quantity and quality conditions, develop Total Maximum Daily Loads (TMDLs), and forecast benefits of new environmental protection policies.

The EPA Water Modeling Workgroup is an internal forum to advance capacity that hosts webinars (> 10,000 attendees, > 29,000 YouTube views), national workshops 2019–2024, and provides modeling support resources. The EPA Center for Exposure Assessment Modeling (CEAM) distributes models across different foci (e.g., surface water, groundwater, TMDLs, food chain, etc.).

The talk highlighted some specific modeling framework examples, including applications of the Visualizing Ecosystem Land Management Assessments (VELMA) Ecohydrology Model, the integrated assessment modeling framework with the Hydrologic and Water Quality System linked with the Benefits Spatial Platform for Aggregating Socioeconomics and H2O Quality (HAWQS-BENSPLASH), and Water Analysis and Simulation Program (WASP) for contaminant fate and transport. One of the EPA's largest integrated modeling efforts is the Chesapeake Bay's coastal watershed modeling with integrated watershed, airshed, and estuary models. The talk notes that EPA IHTM capabilities could be enhanced with collaboration in capturing coastal areas, lakes, wetlands, alpine areas, and the Arctic. Additionally, coordination with other agencies or institutions would be helpful for exploring diverse climate change scenarios, modeling human and natural dimensions, and building capacity to use emerging data science tools.

Laura Condon and Aubrey Dugger—National Testbed Report Out for Session C Breakout

Capabilities – At the national scale, highly valued emerging IHTM capabilities include geospatial fabrics, new computing infrastructures, better integrated software development practices for modeling frameworks, enhanced plug-and-play integration across models, new observational datasets (e.g., the Airborne Snow Observatory), and the ability to expand environmental and social justice applications.

Gaps – The largest identified gaps lie in coordination due to challenges associated with agency silos, gaps between data collectors and modelers, diffuse leadership and governance with no clear community of practice, and incentives to develop "off-the-shelf" capabilities that have a clearer connection to the R2O2R pipeline.

Needs – At the national scale, a core need is the availability of credible models capable of predicting hydrologic conditions in normal and extreme conditions while taking into account human operations and changing conditions. There is a need to better address questions people care about by improving the decision relevance and operational value of modeling efforts. The U.S. government agencies should be a definitive source for national-scale credible and reliable hydrologic information.

A.1.2 Mid-Atlantic Region

Sessions B and C Tuesday (10/31/2023) Mid-Atlantic Testbed – Capabilities, Gaps, and Needs
Session B Speakers: Hedeff Essaid (USGS) and Ian Kraucunas (PNNL)
Session C Breakout Leads: Jeni Keisman (USGS) and Ning Sun (PNNL)

Hedeff Essaid and Ian Kraucunas—Mid-Atlantic Region: Capabilities, Gaps, and Needs

This plenary talk emphasized that the Mid-Atlantic has a broad range of agencies, organizations, projects, and activities seeking to better understand key human and natural systems processes, stressors, and resource management challenges. A few major examples include the Chesapeake Bay Program, the Chesapeake Bay Commission, the Delaware River Basin Commission, and the Susquehanna River Basin Commission. These organizations encompass funding, support, and key interests across federal agencies, state and local governments, non-governmental organizations, and the public. Their roles highlight the institutionally complex challenges in balancing the needs of major cities, such as New York City, Philadelphia, and Baltimore, with the broader suite of multi-sector demands from other smaller communities, agriculture, energy systems, critical ecosystems services, and evolving risks (e.g., droughts, floods, pollution, etc.).

The presenters highlight representative examples of the significant ongoing federally funded research efforts such as the Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA, NOAA), Coastal Observations Mechanisms and Predictions Across Systems and Scales (COMPASS, DOE), Integrated Coastal Modeling (ICOM, DOE), and the Predictive Understanding of Multiscale Processes project of the Integrated Water Prediction Program (PUMP, USGS).

Among these research projects, more detailed examples of IHTM capabilities emerging for the Mid-Atlantic region were provided for the ICOM and PUMP efforts. The DOE ICOM project is advancing research that is contributing new capabilities for better understanding large-scale patterns of extreme events, agent-based modeling of coastal development patterns, regional refinement of Earth system modeling, and watershed-scale extreme event attribution. ICOM is making advances in addressing long-term changes in flooding, drought, hypoxia, and sea-level rise coastal hazards. The system stressors include climate change and its interactions with urbanization, as well as other land use changes.

The USGS PUMP project is addressing the need to advance methods and tools for assessing national and regional water availability. In the Mid-Atlantic, the PUMP project is utilizing the Delaware River Basin as a pilot for advancing regional water availability assessments. The goal is to develop a nationally consistent framework for evaluating past, current, and future water availability trends. There is an emphasis on better understanding drivers of shortages, vulnerabilities across diverse sectoral and ecological water uses, and advancing new capabilities for formulating responses to extreme events. The PUMP pilot regional modeling assessment is bringing together modeling capabilities from national-scale climate and hydrology modeling, regional groundwater modeling, process-guided machine learning for water quality (stream temperature, salinity), managed reservoir systems modeling, and estuary salinity, as well hydrodynamics modeling. Lessons from the PUMP Delaware River Basin modeling are intended to be generalized for other regional water assessments across the U.S. Both ICOM and PUMP represent synergistic investments in IHTM that emerged after IHTM 1.0 that have the strong potential to be leveraged in future efforts.

Jeni Keisman and Ning Sun—Mid-Atlantic Testbed Report Out for Session C Breakout

Capabilities – The Mid-Atlantic has an extremely rich set of existing models and data. There is a strong potential to leverage cross-agency modeling efforts for hurricanes, floods, droughts, salinity intrusion into coastal aquifers, water quality, ecosystems health, and long-term water availability assessments given climate change and growing multi-sectoral demands.

Gaps – One of the largest identified gaps is the general lack of awareness and coordination of IHTM-relevant efforts across institutions, agencies, and researchers. As an example, the Chesapeake Bay Model Inventory and Selection Tool by itself identifies more than 100 models addressing concerns from watersheds to the coastal estuary. There are also a broad range of data gaps related to human demands, water quality, and water management operations.

Needs – Enhance IHTM capability outcomes to give Mid-Atlantic decision-makers a better understanding of the utility and cost-effectiveness of management options for regional planning, management of evolving hazards, and improving water quality and ecosystem services holistically. Interagency efforts are needed to include shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and improved open science protocols.

A.1.3 Upper Colorado River Basin

Sessions B and C Tuesday (10/31/2023) UCRB – Capabilities, Gaps, and Needs
Session B Speakers: Dave Gochis (NCAR) and Rob Cifelli (NOAA)
Session C Breakout Leads: Lejo Flores (Boise State University) and Ben Ruddell (Northern Arizona University)

Dave Gochis and Rob Cifelli—Upper Colorado River Basin Region: Capabilities, Gaps, and Needs

This plenary talk highlighted that there are several major R2O2R efforts that are ongoing in the UCRB related to improving prediction of weather and water in the complex, mountainous terrain of the basin (Figure A.2). The Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) is the NOAA component of a broader interagency field campaign that also includes the DOE Surface-Atmosphere Integrated field Laboratory (SAIL), as well as efforts by NSF-supported universities. SPLASH has goals to evaluate NOAA operational forecasting, improve understanding of land surface and boundary layer processes in mountainous terrain, advance fundamental knowledge related to mountain cloud and precipitation microphysics, and better characterize interactions between large-scale circulations and meso/microscale features (e.g., local impacts of El Niño–Southern Oscillation/ Madden-Julian Oscillation or the effects of inland penetrating atmospheric rivers on the region). The SPLASH project is facilitating interactions between the National Weather Service and the Bureau of Reclamation to better understand forecasting challenges. The effort is advancing emerging capabilities for in situ and remote sensing observations to better characterize surface, boundary layer, and precipitation processes. This includes coordination with the Sublimation of Snow Field campaign, where NSF has supported numerous flux towers, snow pillows, and other in situ sensors. The hydrometeorology of the UCRB is critical to the complex water resources decision-making confronting the overall Colorado River.

The second R2O2R focus highlighted in this plenary talk was on the recent emergence of major water prediction and assessment capabilities in UCRB. Several flagship modeling efforts are focused on assessments and forecasts for the region. Examples include NOAA forecasting with the operational National Water Model, as well as the river forecasting centers; the USGS water availability assessments using the National Hydrologic Model, including new CONUS-404 forcing datasets; the U.S. Drought Monitor multi-model and observational data assimilation products; and the Colorado Airborne Snowpack Monitoring Program to inform seasonal water supply forecasts. New airborne-lidar snowpack monitoring and gap-filling radars are having major impacts. The Humans and Hydroclimate in the United States (H2US) Project offers a multi-agency, multiscale framework for advancing IHTM in the UCRB. While these efforts and capabilities are promising, several key challenges are also highlighted. There are quality and latency challenges in forcing observations, seasonal forecasts are very uncertain, and there are challenges in operationalizing emerging observational field campaigns. Other major IHTM challenges in the UCRB are related to the need to better capture the dominance of human-mediated management of the system's flows, as well as its highly dynamic landscapes (e.g., wildfires, agriculture, and urbanization).

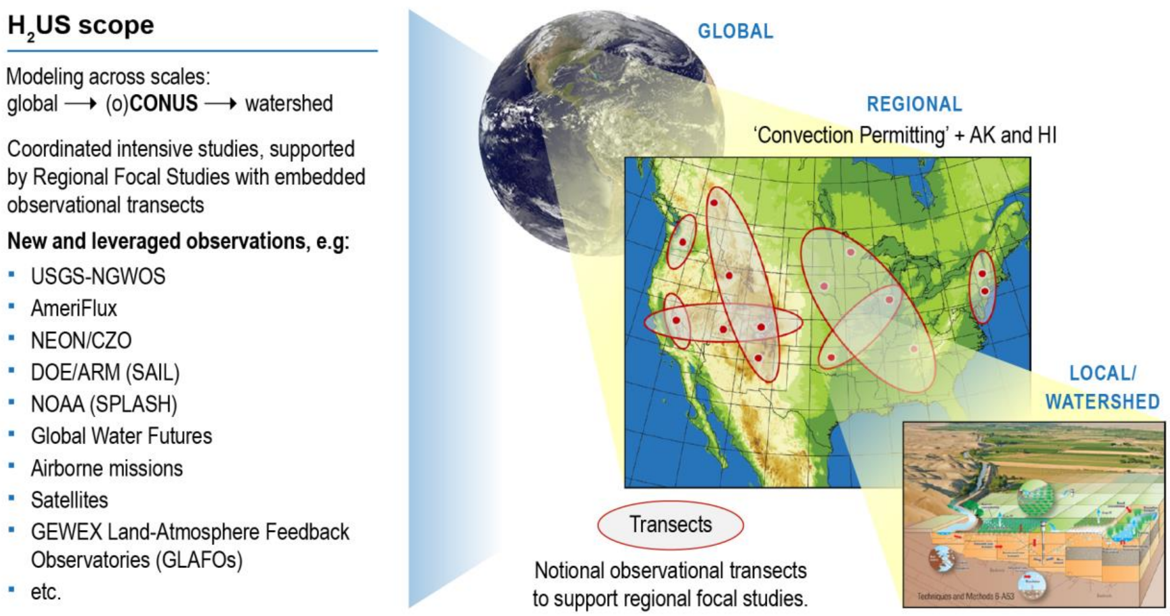

Figure A.2. Coordinated research under the new Global Energy and Water Exchanges (GEWEX) Humans and Hydroclimate in the United States (H2US) Regional Hydroclimate Project (source: T. Schneider and R. Cifelli).

Lejo Flores and Ben Ruddell—UCRB Testbed Report Out for Session C Breakout

Capabilities – The UCRB and its relationship with the broader Colorado River represents one of the most heavily managed, modeled, and impactful basins in the world. Consequently, there is a uniquely diverse range of existing models, and the region is data rich. Multiple agencies have established regional testbeds and there are a growing number of monitoring campaigns, as well as innovations in piloting emerging observational technologies.

Gaps – One of the largest identified gaps is aligning incentive structures to enable participation in coordinated IHTM activities by multiple agencies (federal, states, and tribes) with different missions, as well as federal labs and university researchers. In terms of the R2O2R contributions, there is a need for better mechanisms for managers and decision-makers to be involved in evaluating and informing major modeling activities. Human systems, governance, and institutions remain poorly resolved in many modeling frameworks.

Needs – Enhance IHTM capability outcomes to give UCRB decision-makers a better understanding of the long-term growing drought risks with climate change and the allocative challenges of the basin. Better coordination mechanisms are needed for shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and improved open science protocols. Develop near-term opportunities for collaborations that leverage existing major federal efforts.

A.1.4 Great Lakes Region

Sessions B and C Tuesday (10/31/2023) Great Lakes Testbed – Capabilities, Gaps, and Needs
Session B Speakers: Rob Hetland (PNNL) and Debbie Lee (NOAA)
Session C Breakout Leads: Venkatesh Merwade (Purdue University) and Rebecca Muenich (University of Arkansas)

Rob Hetland and Debbie Lee—Great Lakes Region: Capabilities, Gaps, and Needs

This plenary talk on the Great Lakes highlights DOE and NOAA efforts seeking to better understand coastal freshwater systems and their interactions with human systems, specifically around water quality and regional climate dynamics. The GLR is prone to extreme events (e.g., extreme lake-effect snow, summer storms, heat waves, floods, and droughts), as well as major water quality challenges (e.g., harmful algal blooms and hypoxia) that strongly disrupt dependent human system activities. These challenges emerge from complex and interdependent processes involving climate, hydrology, ecosystems, and human systems across a wide array of scales. The DOE Coastal Observations Mechanisms and Predictions Across Systems and Scales – Great Lakes project (COMPASS) is advancing research focused on developing and analyzing coupled regional Earth system models to better understand the co-evolution and interdependencies of coastal regional processes and human systems in the Great Lakes. COMPASS-Great Lakes is utilizing regional integrated models to study atmospheric-lake heat exchanges and the influence of land surface temperature on regional climate and weather, while high-resolution watershed modeling, along with dynamic human systems representations (agricultural practice), help address small-scale watershed processes impacting water quality in the lakes.

As another example, the NOAA Great Lakes Environmental Research Laboratory (GLERL) addresses the complex human-natural systems that compose the Great Lakes from an explicit R2O2R perspective. GLERL focuses on transitioning fundamental science innovations into operations through the whole chain necessary to promote mission-oriented products: Observations, Experiments, Concepts, and Models/Applications. Recent efforts are advancing an integrated Great Lakes modeling system to improve forecasts of lake hydrodynamics, lake ice, hydrological response, ecological processes, water quality, climatic variability, and near-term to long-term trends or changes. The goal is to have linkage to the NOAA Earth system modeling initiative and Unified Forecast system. To meet the operational expectations, each lake has its own forecast system (Lake Superior, Michigan-Huron, Huron-Erie, Erie, Ontario), which includes a diversity of models and observations: the National Water Model, the Global Forecast System, the Water/Ecology, Harmful Algal Bloom Forecast System, Regional Weather High-Resolution Rapid Refresh, Wave Watch 3, and the Great Lakes Operational Forecast System-ICE.

The speakers highlight across the DOE and NOAA examples of the opportunities for valuable collaborations since each effort lies at a different stage the R2O2R roadmap (see Using a Technology Readiness Map to Help Identify R2O2R Opportunities in IHTM and Figure 3.2) where NOAA could provide critical data and DOE could provide large computational resources so that both efforts can advance understanding, modeling, and prediction of complex extremes and water quality challenges.

Venkatesh Merwade and Rebecca Muenich—Great Lakes Testbed Report Out for Session C Breakout

Capabilities – The GLR captures more than 20 percent of the world’s freshwater. Current IHTM efforts bridge many cooperative entities (local communities, multiple states, and Canada) and broad governing bodies (e.g., the International Joint Commission). The system has many existing models and significant data resources, such as high-resolution stream water quality data (daily, 40+ years), lake evaporation, and lake temperature, as part of a 40-year reanalysis dataset.

Gaps – Major identified gaps are the representation of major human systems (e.g., reservoirs, farmer data, etc.) and modeling frameworks capable of capturing the entire region. Integrated full regional models face data constraints, international collaboration challenges, and broader capacities to run large-scale modeling workflows (e.g., staff as well as computing).

Needs – Highly valued advances in IHTM capabilities for the GLR would be improved whole region workflows to create high-resolution modeling frameworks that bridge Earth system to local scale dynamics. There is a strong potential for bridging the strengths of research agencies (e.g., computing support) and operational agencies (e.g., comprehensive monitoring datasets) to strengthen their individual as well as collective advances.

A.1.5 Mississippi/Gulf Coast Region

Sessions B and C Tuesday (10/31/2023) Mississippi/Gulf Coast Testbed – Capabilities, Gaps, and Needs
Session B Speakers: Lauren Schmied (Federal Emergency Management Agency [FEMA]) and John M. Johnston (EPA)
Session C Breakout Leads: Jodi Ryder (USACE) and Adam Schlosser (Massachusetts Institute of Technology)

Lauren Schmied and John M. Johnston—Mississippi/Gulf Coast Region: Capabilities, Gaps, and Needs

The plenary talk highlighted two agency perspectives on IHTM advances in addressing flood risks and Gulf hypoxia. FEMA is providing more comprehensive flood hazard and risk data by advancing the Future of Flood Risk Data (FFRD) framework where, for inland riverine hazard and risk, there is a shift to a 2-D-based watershed-wide approach that leverages observed, gridded precipitation, as well as stochastic storm transposition to represent the range of possible flood responses. For coastal regions, the FFRD framework is producing probabilistic flood hazard risk data based on 2-D modeling and a statistical framework built jointly by USACE and FEMA using probabilistic coastal zone analysis. The framework itself relies on the parameterization of tropical cyclones to represent possible realizations and relies on high volumes of simulations, meta-modeling, and other processes to be able to quantify the overall uncertainty from the probability of various coastal hazard responses. These data are processed at very high spatial resolution and currently focused on Louisiana and Texas. FEMA's eventual goal is to provide comprehensive hazard and risk data at high resolution for partnering across agencies, academia, and the private sector, while working to empower stakeholders with actionable information.

The second R2O2R perspective draws on EPA's efforts in addressing climate change and land use change (including crop management practices) effects on hypoxia in the Gulf of Mexico, which has the second largest dead zone in the world. To address this challenge, the agency has advanced the Gulf Hypoxia Multimedia Modeling Framework (Figure A.3) where climate change scenarios drive the Weather Research and Forecasting (WRF) Community Multi-scale Air Quality (CMAQ) to project atmospheric nitrogen deposition for the inland river basin and coastal regions. The framework captures coastal water quality using the Coastal Generalized Ecosystem Model (CGEM) and inland nutrient dynamics using a high-resolution Soil & Water Assessment Tool (SWAT) representation of the Upper Mississippi River Basin. Additionally, ocean hydrodynamics from the Hybrid Coordinate Ocean Model (HYCOM) are provided to CGEM and the Fertilizer Emission Scenario Tool (FEST-C) provides fertilizer land applications for SWAT. In combination, these models allow the Gulf Hypoxia Multimedia Modeling Framework to provide an integrated ecosystem assessment that bridges crop production, nutrient runoff, irrigation water demand, and fertilization, as well as air and water quality. Broadly, the EPA R2O2R hypoxia management capabilities enable informed regulatory management between state and federal waters, forecasting responses to management actions, and a better understanding of the carbon dynamics that impact hypoxia in the Gulf Coast/Mississippi region.

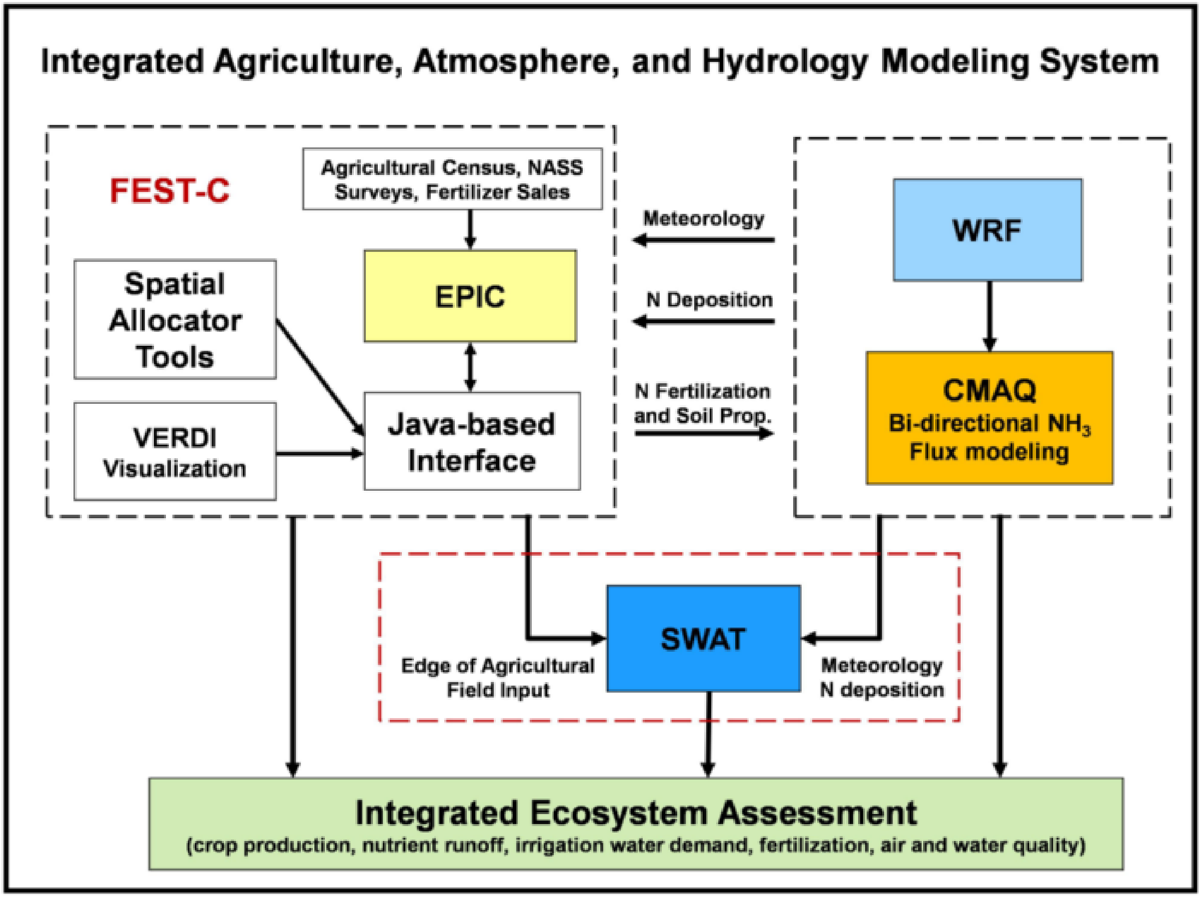

Figure A.3. Integrated Multimedia Modeling Framework designed to address effects of land use/land management and climate changes on nutrient loss (source: Ran et al., 2019, Figure 1).[1]

Jodi Ryder and Adam Schlosser—Mississippi/Gulf Coast Testbed Report Out for Session C Breakout

Capabilities – The Gulf Coast/Mississippi Region is the largest U.S. river basin, with intensive federal, state, local, and tribal efforts shaping its management. It has a critical role in navigation as well as a dominant impact on the national economy and global trade. The system has a broad array of existing IHTM capabilities addressing extremes (floods, droughts, hurricanes, sea-level rise), water quality challenges, and the complex feedbacks with the human systems it supports.

Gaps – One of the largest identified gaps is the lack of consistency in representing the multi-sectoral demands, water requirements, and risk targets across the array of challenges facing the region. Overall data on these issues are sparse given the scale of the entire drainage area

[1] Ran, L., Y. Yuan, E. Cooter, V. Benson, D. Yang, J. Pleim, R. Wang, and J. Williams. 2019. “An Integrated Agriculture, Atmosphere, and Hydrology Modeling System for Ecosystem Assessments.” *Journal of Advances in Modeling Earth Systems* 11 (12): 4645–4668. https://doi.org/10.1029/2019MS001708.

of the Mississippi River where key smaller features (e.g., wetlands) are not well resolved. This poses challenges balancing decision relevance for stakeholders, appropriate levels of model complexity, and uncertainties in model-based analyses.

Needs – Highly valued advances in IHTM capabilities for the Mississippi/Gulf Coast Region would be improved infrastructure for shared data and model repositories, formal community benchmarking for different models, coordination on consistent scenario development and use, and guidance on handling data confidentiality concerns that emerge across different application areas. Formal IHTM model intercomparison projects hold significant promise. There would be high value for near-real-time model maintenance, support for rapid deployment of workflow configurations, and computational support of large-scale risk assessments.

A.2 Key Challenges for the Design of IHTM Testbeds

Session E Wednesday (11/1/2023) Key Science & Methodological Challenges
Science Challenges Speakers: Ruby Leung (PNNL), Alison Appling (USGS), and Nathalie Voisin (PNNL)
Methodological Challenges Speakers: Chris Vernon (PNNL), Roland Viger (USGS), Martyn Clark (U Calgary), Christopher Dunn (USACE), and Jordan Read (CUAHSI)

Ruby Leung—IHTM 2.0: Major Challenges in Hydro Extremes

This plenary talk highlighted the importance and regional diversity of major hydro-terrestrial extremes. Floods, droughts, and wildfires are increasingly causing billion-dollar weather and climate disasters that are widely impacting regions across the U.S. A major challenge for understanding and predicting these events is that their underlying driving processes are evolving with climate change, human activities, and vegetation dynamics. The drivers of flooding include combinations of heavy and persistent rainfall, climate-ocean circulation patterns, initial soil moisture conditions in a catchment, and the confluence of flood waves through the river system.

Recent IHTM advances highlighted the structural changes in storms under global warming, motivating the need for analysis of event-scale precipitation. Cold season storms are not only becoming more intense, but their precipitation is becoming more spatially concentrated, causing increasing vulnerabilities of infrastructure to both flash floods and slow-rising floods. While storm and precipitation changes under warming may increase flood risk, water management systems could potentially alleviate future floods, but many sources of uncertainty in modeling floods and water management limit our ability to evaluate the combined influence of climate change and water management on flood risk in the future.

Land cover changes (e.g., urbanization) are often reducing infiltration, interception, and evapotranspiration processes, yielding more runoff generation and, thus, enhanced flood risks. Drought extremes vary depending on their classification and the end use focus of their impacts—meteorological, agricultural, hydrological, or biophysical. While some drivers are well constrained, like temperature, humidity, snowpack, and vapor pressure deficit, precipitation and evapotranspiration remain the most uncertain drivers (Figure A.4). Recent work also highlights vegetation as a critical driver for regulating evapotranspiration and drought dynamics. Wildfires emerge as part of complex cycles between floods and droughts. They also can serve as drivers that compound the effects of flood and drought extremes (e.g., changes in the landscape from fires that exacerbate catastrophic flooding for human systems).

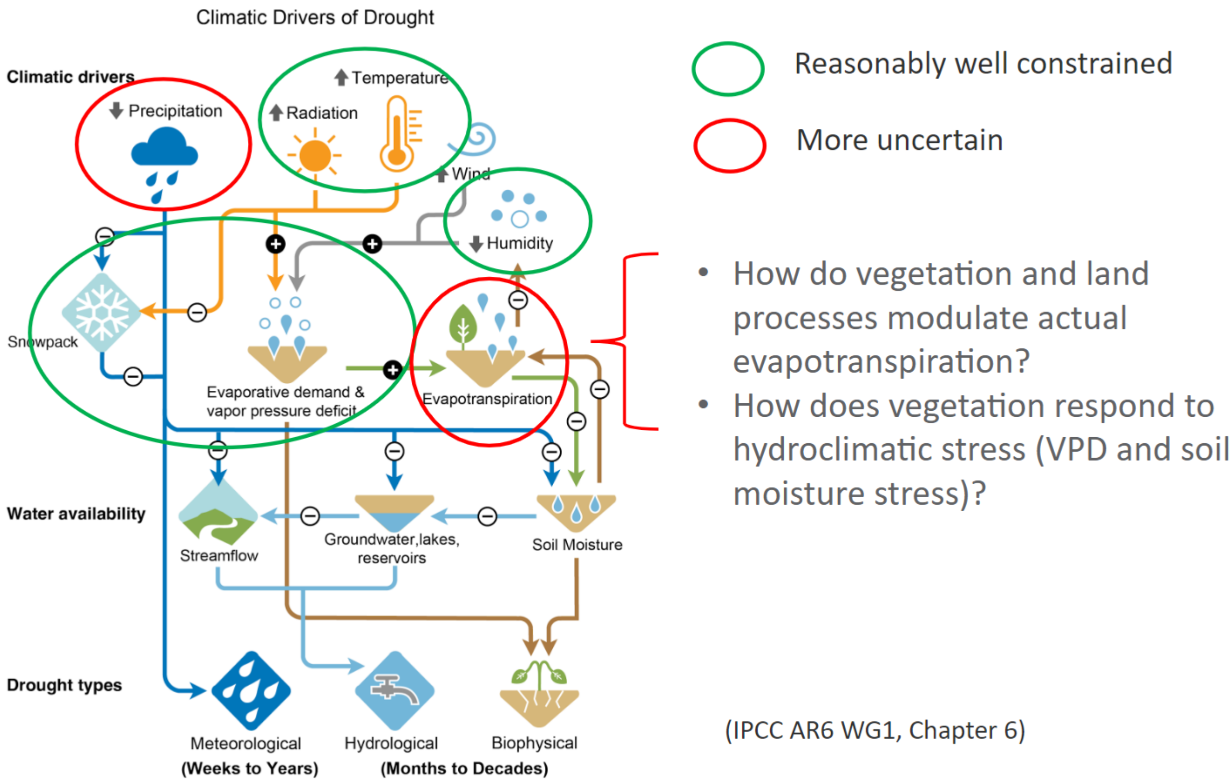

Figure A.4. Changes in climatic drivers affect the hydrologic cycle, which translates into changes in different drought types (source: IPCC AR6 WG1, chapter 6, adapted by R. Leung).

Alison Appling—Water Quantity, Quality, & Use: Themes & Challenges for Integration

This plenary talk emphasizes key foci of integration for IHTM 2.0 to realize its potential for providing major societal benefits through interagency and academic collaborations (see Science by Design – Integration as the Focus for Testbeds and Figure 3.3). The suggested integration foci are (1) Data Resources, (2) Staff/Science Expertise, (3) Understanding the Interactive Effects of Drivers, (4) Exploring Key Feedbacks in Dynamics, and (5) Aiding Society to Better Balance Risk-Benefit Tradeoffs.

Many research and operational agencies have mandates that are both national in scope and that use regional testbeds to further advance IHTM capabilities toward better meeting societal needs, advancing science, and innovating technical workflows. The talk highlights the USGS as an example where the agency's national assessments evaluate water availability, its quality, and supply vulnerabilities. While addressing the national scale, the USGS is also exploring complementary use of regional testbeds to better capture the key dynamics and specific challenges that emerge at more local scales. USGS regional testbeds include the Willamette River Basin, focusing on stream temperature and ecosystems; the Upper Colorado River Basin, focusing on water availability, snow, and salinity; the Trinity-San Jacinto River Basin, focusing on floods and urbanization; the Illinois River Basin, focusing on harmful algal blooms and nutrient transport; and the Delaware River Basin, focusing on water availability, salinity, and water temperature.

These regional testbeds augment the national USGS water availability assessment by designing them to achieve three key features: comprehensiveness, forward looking, and locally capable. Comprehensiveness specifically includes relevant spatial and temporal resolution and coverage. Forward-looking implies realistic and diverse long-term scenarios complemented with timely short-term forecasts. And locally capable supports the development of enhanced local applications. The USGS is advancing IHTM capabilities that include complex couplings of models across scales that are forward looking for future horizons being evaluated using locally relevant metrics. The presentation uses the USGS example to frame the broader potential for IHTM 2.0 to explore interactions between societal needs, science questions, and methodological challenges to make needed advances.

Nathalie Voisin—Water Quantity, Quality, & Use: Themes & Challenges for Integration

The plenary talk addressed how human systems interact closely with water systems: water withdrawals, land use, reservoir storage and release operations, groundwater pumping and streamflow enhancement, and runoff pathways such as conveyances and tile drainage. Recent scientific advances supported by the DOE Office of Science, Water Power Technologies Office, and NSF include the development of large-scale water management—reservoir operations using data-driven operating rules, which supports consistent modeling across CONUS. Sectoral water demands are being developed by USGS and projections by the DOE Office of Science. Simultaneously, DOE applied offices analyze changes in water demand associated with technology innovation and adoption incentives and conservation programs. Other advances include resolving user-level drought impacts, exposing how drought intensity is modulated by water management institutions (e.g., Prior Appropriation water rights in the U.S. West).

Accounting for these institutions is important for understanding the complex water scarcity tradeoffs across competing sectoral users. Generally, a realistic representation of human systems in integrated hydro-terrestrial models is needed to achieve substantial advances. Human systems interact with the water cycle and each other across scales, via their organized and evolving demands/uses. A current R2O2R challenge for IHTM is addressing the dual roles that human systems have as both consumers of climate services, as well as agents of changes that shape broader-scale dynamics. The relevance of operations (the “O”) as both a response to needs and a potential driver of longer-term, larger-scale change holds significant value for the research community (the “R”). The presenter recommends to carefully define human systems not solely through the perception of needing climate/IHTM services, but also in their role as drivers of change in hydro-terrestrial science and as a means to test the generalization of human systems representations in modeling strategies across testbeds (national and regional).

Chris Vernon—Open Science and Community Building: IHTM 2.0 Realizing Ideas and Setting the Stage

This plenary talk emphasized the importance of carefully formulating a shared vision for transitioning from choosing IHTM science questions (“what to focus on”) to enabling functioning, production-ready workflows that can be collaboratively advanced by the community. The commitment to open science is critical to fully realize the benefits of diverse expertise, emerging insights, and accelerating the IHTM community in making major advances.

Examples for open science and community building were drawn from the recent establishment of the MSD Community of Practice (CoP) supported by the DOE Earth & Environmental Systems Science Division. Since 2019, the MSD CoP has established a core facilitation team to organize community-level efforts and a science steering group to continually identify new opportunities to better address the interdependent risks and resilience of human-Earth systems. Additionally, the MSD CoP has established scientific working groups in key challenge science topics, building a more diverse community, and facilitating open science. In 2022, the MSD CoP published an organizing vision for research challenges and made open science, as well as Findability, Accessibility, Interoperability, and Reusability (FAIR) principles, central to community goals. Initially, the MSD Open Science and FAIR Data working group sought to foster a culture of openness and facilitate a collaborative, resource-rich community. The value and impact of the working group as a central means of advancing the entire MSD community of researchers led to its transition to MSD-LIVE (Living Intuitive Value-adding Environment). MSD-LIVE provides a data and code repository, project support services, and computational resources for major modeling efforts. It plays a key role in supporting broader training in FAIR principles and allowing for reproducible complex multi-model workflows. It has broadened the MSD community's ability to share major data and modeling resources to other communities. The underlying infrastructure also positions the MSD CoP to leverage future emerging technologies for supporting open science data sharing and next-generation artificial intelligence (AI) workflows.

Roland Viger—The "How": Methodological Themes and Major Challenges

This plenary talk detailed workflows and model benchmarking as critical components of community modeling. The setup of model applications, including pre-processing, calibration, and exploration, as well as running model applications and evaluation of model applications' results, are all dependent on transparent workflows that others can use.

In terms of community modeling, there is a vast array of options to choose from with respect to computational problems, software packages, and computing environments. The talk described the USGS and NCAR Hydro-Terrestrial Earth Systems (HyTEST) project as a resource to support workflow and model benchmarking choices. HyTEST focuses on using community-adopted standards, tools, and approaches, all of which are scalable by design and enable reproducibility on an infrastructure that is accessible to all. HyTEST is highlighting the limits of USGS's current internal capability for migrating large datasets, as well as the network limits. Consequently, HyTEST is taking a cloud-centric approach where computing becomes a commodity. Additional advantages include that it is available for whatever is needed, whenever it is needed. It works well for both big and small data and the user pays only for what they use. This enables development and advancement at all institutions, not just the privileged ones with a wealth of computing resources. The cloud is both open and robust: data can be accessed without additional data services. Development on the cloud encourages the use of standards and best practices and supports open science. The Advanced Scientific Computing roadmap of the HyTEST project first seeks to support the computing needs of the entire simulation workflow, interactive analysis and visualization, and operational workflow pipelines. They seek to follow architecture patterns that are already succeeding in the open-source geospatial and modeling communities and, finally, integrate with and extend existing tools, practices, and frameworks.

Additionally, HyTEST is evolving the International Land Model Benchmarking (ILAMB) scorecard as an approach to guide the model evaluation process in a manner that standardizes the application of a set of statistical methods to simulated model output and observations (or other datasets held as representing "truth") to generate a result of performance for modeling applications. This talk concludes by suggesting that, for testbeds to progress, the "what" requires refinement, and the "how" to support modeling requires overcoming institutional barriers. Additionally, IHTM participating agencies and institutions need improved communication and synchronization of efforts, as well as shared governance.

Martyn Clark—An Inter-agency Community of Practice: The Model Ecosystem, Interoperability, and Connection between Science and Software

This plenary talk explores the challenges and opportunities posed in establishing an interagency IHTM CoP for hydrologic modeling. The major themes include engaging realistically with the diverse model ecosystem, acknowledging the importance of interoperability standards, and carefully considering the deep connections between science and the software systems that support it.

The importance of establishing a broader CoP is emphasized in this talk through the challenges that IHTM encompasses: a broad array of models, application foci, and their underlying research or operational communities. The talk suggests caution in thinking through the lens of a "one-size-fits-all" community model or single modeling framework. Further, the talk suggests that the development of a IHTM CoP becomes tenable when it is recognized that (1) different models have similar data requirements and, potentially, process representations; (2) there is broad value in sharing code, workflows, and concepts across different modeling communities; and (3) there is a need to put more focus on modeling frameworks, their communities, and the people needed to support them versus any individual model (Figure A.5).

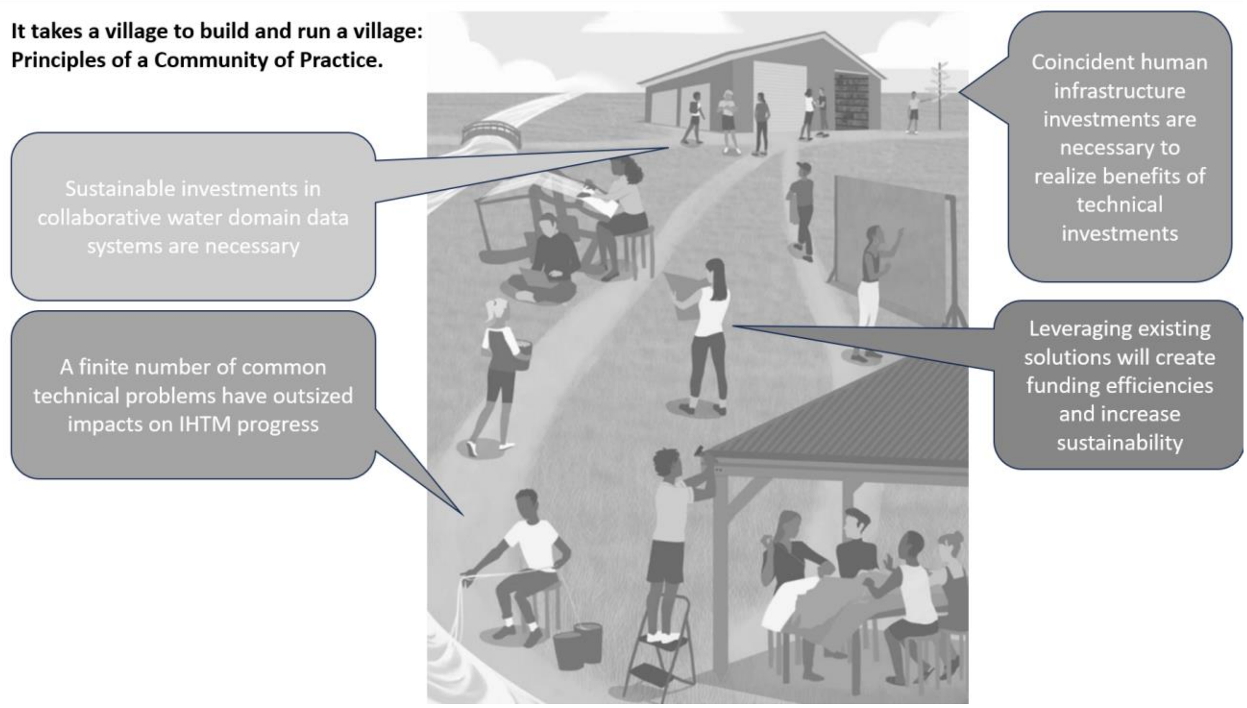

Figure A.5. Principles of a CoP. IHTM, whether a distinct and/or subset of existing CoPs, would help address the pressing needs of the nation (source: J. Read, adapted by N. Voisin).

The bottleneck for accelerating IHTM advances is noted to not be solely a technical or scientific limitation, but rather community-level limits in reproducibility in models, data, and workflows.

More general model-agnostic workflows offer an approach to keep model-specific requirements out of the data processing chain for as long as possible to realize major interoperability and efficiency gains. An example is provided by the NOAA Office of Water Prediction NextGen water resources modeling framework. The NextGen framework seeks to run multiple models of different type and complexity across large geographical domains, use basic model interfaces to allow multiple modeling approaches to be run within a single framework, enable representing processes across different space and time scales within an integrated modeling framework, and unify different modeling groups to contribute their expertise and pool resources. Major recommendations for next steps include thinking tractably about IHTM. It is suggested that IHTM should be engaged as multiple overlapping CoPs that address critical problems (e.g., forcing data, geospatial fabrics, workflows, mechanistic models, parameter inferences, uncertainty quantification, visualization, etc.). As part of these communities, universities offer the opportunity to serve as “the glue” that connects efforts across multiple federal agencies through long-term relationships. Finally, IHTM should be framed in its global context, because the U.S. is not unique, and breakthroughs will be accelerated by connecting to other modeling groups around the world.

Christopher Dunn—IHTM 2.0: Research to Operations to Research

This plenary talk clarifies that, to effectively span the space from R2O2R and the evolution of products to address changing needs, there is a critical need to be clear on both the what and the why before the how can be addressed. The “What” or the core mission of the USACE is to manage the nation’s water resources. The Corps Water Management System (CWMS) is used for real-time decision support for water management and ensures consistent operation across 36 offices. This includes more than 700 multipurpose reservoirs, flow control structures, and thousands of miles of levees and other structures. The goal is to achieve the full range of authorized purposes from all USACE projects, which includes floods to droughts and everything in between.

In 2014, the national map of implementation of CWMS was very incomplete, with only 16 basins completed out of 201 watersheds across the U.S., in places where USACE has water management responsibilities. The goal of the R2O2R is to move those other basins into the CWMS framework. The USACE Hydrologic Engineering Center (HEC) develops new procedures and programs that meet the changing needs of USACE, the country, and the profession and that utilize new science and technology. This is essentially bringing the “state-of-the-art” into “state-of-the-practice.” This can include the leading edge from universities, federal partners, or essentially anywhere, so that the modeling system of USACE is more intuitive, faster, and more automated; has improved graphics; is both stable and familiar; is robust; and has better diagnostics.

Through that R2O2R process, USACE has moved from the map in 2014 to the current national implementation, where approximately 76 percent of the country has hydrology models (HEC-HMS), hydraulics models (HEC-RAS), reservoir models (HEC-ResSim), and consequence models (HEC-FIA). This enables planning studies and real-time studies. This represents significant progress over the course of a decade.

The CWMS system can be transitioned to planning through the development of additional software, including HEC-WAT, the Watershed Analysis Tool. This is currently a desktop application with distributed compute option, but it is being pushed to the cloud. HEC-WAT is one of the very few system-based risk analysis capabilities. It incorporates CWMS and the HEC software and existing models. It contains a nested Monte Carlo approach that captures both natural variability and uncertainty. It can be used with small drainages (< 100 square miles) up to Columbia and Missouri Rivers. The HEC platform has a wealth of free training and documentation, as well as technical assistance available online (Discourse). However, the open-source aspect is a security challenge.

Jordan Read—Community Focused Infrastructure for Advances in Water Modeling

This plenary talk discusses how the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is focused on helping to create the ecosystem of technical infrastructure to meet water research needs and the cultural and community-focused shifts needed to advance IHTM.

The community has made progress in creating open data, but this is still a challenge. There is still a need for the critical infrastructure necessary to work together. Data and computers have a great deal of organizing gravity, and how those systems are structured can dictate how we collectively collaborate on the science itself. There are four common challenges that face the IHTM community: (1) establishing collaborative data systems, (2) prioritizing efforts on common technical problems, (3) leveraging existing solutions, and (4) investing in human infrastructure. There is a foundational need for better collaborative data and computing environments. The collaborative data systems can serve as a convening place that is critical for bringing people together to work on common technical problems.

There are several common technical problems in the IHTM community, one of which is basic data management. There is a need to get more field data through the process into a product that becomes generally available for use and reuse. Another possible common technical problem is that of data interrogation or visualization. How can we dig into large, complex datasets and identify issues or agree upon things like score cards or different metrics of performance for our models? Reproducibility is another common problem, and its role in training and making efforts sustainable and long-lasting needs to be acknowledged.

With respect to leveraging existing solutions, the IHTM community needs to consider building bridges to other communities as better answers may exist outside of the community or adjacent to it. With respect to the human infrastructure, the people that work on the infrastructure, in addition to the people who are working on the collaborative products, need equal support. The community needs to consider the tiers of reproducibility and the human infrastructure needed to support that reproducibility. Workflows are now an established expectation to demonstrate reproducibility. There is still a wide range in reusability and maintained documentation of the workflows. There is a critical need to invest in technologists, trainers, and coordinators that engage the community, as well as to help establish new baseline skills. Celebrate and reward the diversity of professional water roles.

There is a need for more agency collaboration and joint training when developing water domain data and modeling systems. Reduce the friction and stigma of solution reuse, balance innovation with efficient reuse, and examine the incentives that only reward custom solutions.

Appendix B – Testbed Visions and Next Steps

B.1 U.S. National Testbed

Lead authors: Lauren Lowman (Wake Forest University), Yadu Pokhrel (Michigan State University), Laura Condon (University of Arizona), Aubrey Dugger (NCAR), Charles Luce (USDA Forest Service), Tim Schneider (NCAR), Roland Viger (USGS)

B.1.1 National IHTM Potential Capabilities

For the IHTM national testbed to provide high value, its capabilities must advance the science of hydrology. First, it must have the ability to be evaluated carefully across a broad range of hydrologic processes under normal and extreme conditions, considering both natural and human dynamics, and across multiple timescales and forecasting horizons. Most current models perform well under average conditions but struggle to consistently simulate extremes. National-scale hydrologic models generally include advanced treatment of natural processes but only simplistic treatment of anthropogenic drivers (e.g., reservoir operation, irrigation, groundwater use), if included at all. By developing integration strategies with more refined regional data and models across diverse application contexts, the national testbed has the potential to address fundamental process-based gaps that persist in IHTM.

Specifically, the IHTM national testbed can aid in breaking down barriers that currently exist in (1) free exchange of knowledge across government agencies and academia and (2) training of individuals from diverse backgrounds. To aid in knowledge exchange, the national testbed should provide unified and more reliable data for model input and share outputs in a standardized way. These input/output (IO) capabilities will minimize redundancies, enhance end-user utility, and accelerate R2O2R. Further, standardized IO will synergize the development of model harmonization and benchmarking platforms (e.g., International Land Model Benchmarking), aided by workflows, geofabrics, and topologies. Such common platforms could consider representative basins that span different climate, terrains, land uses, and degree of water management. To support community training and use, workflows within the national testbed need to be interoperable to allow individuals from diverse backgrounds to run the models and work with data outside of their core disciplines/expertise. By providing a platform to freely share models, data, and ideas, the testbed will make integrated modeling more accessible, leading to accelerated scientific productivity and a diversified workforce.

B.1.2 National IHTM Capabilities for Interagency and Partner Collaboration

To enable interagency and partner collaborations, IHTM must provide clear structural guidance around how agencies and individuals will engage with the national testbed and provide technical support for collaborative outcomes. IHTM capabilities should facilitate secure and direct exchange interfaces to share outputs in real-time for operational purposes. Technical capabilities that will enable collaborative advances in the national testbed include standards for benchmarks, interfaces, and ontology; the creation of a common digital hub where data, model codes, model applications, workflows, and knowledge may be freely shared; and physical resources (e.g., data storage/sharing and computing). Human resources to ensure the successful implementation of all capabilities will be crucial to the success of the testbed. These human resources include dedicated time for agency staff to engage, mechanisms to support active contributions from universities, stakeholders, and other community members, and rewards (“carrots”) for both leadership and followership.

Methodological capabilities of the national testbed refer to both the capabilities of the testbed to provide a collaborative workspace and the capabilities of the models and data to represent the complexity of national water systems. Collaborative workspace requirements include: (a) experts in data library/curation to provide guidance on preparing datasets, metadata, and model configurations; (b) model experts distilling relevant model information, assumptions, and uncertainties for end-users; (c) advisors from the different disciplines contributing datasets to define suitable data uses and limitations; (d) common data formats and geofabrics; (e) interfaces for building connections between models; (f) common and standardized benchmarking criteria, inputs, and protocols; and (g) easy-to-find and easy-to-use data search catalogs. Models and data within the national testbed must consider human, natural, and operational/water management components. For this, the regional testbeds can be used to span different climate, terrain, land use, management, and dominant physical hydrologic processes to aid the evaluation of the robustness of key elements of the national testbed.

Projections of future conditions, including the impacts of extreme and compounding events, can be assessed using computational experiments (at both national and regional scales), in which models of system functioning (e.g., water quantity, water quality, water use) are driven by inputs obtained from scenarios for atmospheric forcings, land cover, land use, and management strategies. These scenario-driven inputs are typically obtained from downscaled climate models, but they can also be obtained using stochastic weather generators, pseudo-global warming approaches, or other types of emulators. The models of system functioning, which can be process-based, data-driven, machine learning, or combinations thereof, are tested and calibrated using the observed historical record. By learning from the past, models of system functioning can be used to evaluate the impacts of potential stressors of the future, identify system tipping points and failure modes, explore management strategies to avert bad outcomes, and illuminate more sustainable and resilient development pathways.

Operational prediction of shorter-term system behaviors (daily to seasonal) and the impacts of extreme and compounding events also rely on models of system functioning (e.g., streamflow and water quality prediction models), which are tested and calibrated using the observed historical record and driven by meteorological weather forecasts (daily to seasonal) and all of the other required input model variables. In these applications, the models of system functioning are configured to capture the current structure of land systems (static land). In an operational context, the predictive skill of these models is critically dependent upon the accuracy of the inputs, especially the weather forecasts used to drive the models and the data assimilation approaches utilized in the operational prediction schemes.

In both applications, the models must be effective outside of the parameter estimation range to provide predictions of future conditions and extreme events not reflected in observed data record. Figure B.1 describes the core national testbed components and how research and local and regional efforts might plug in.

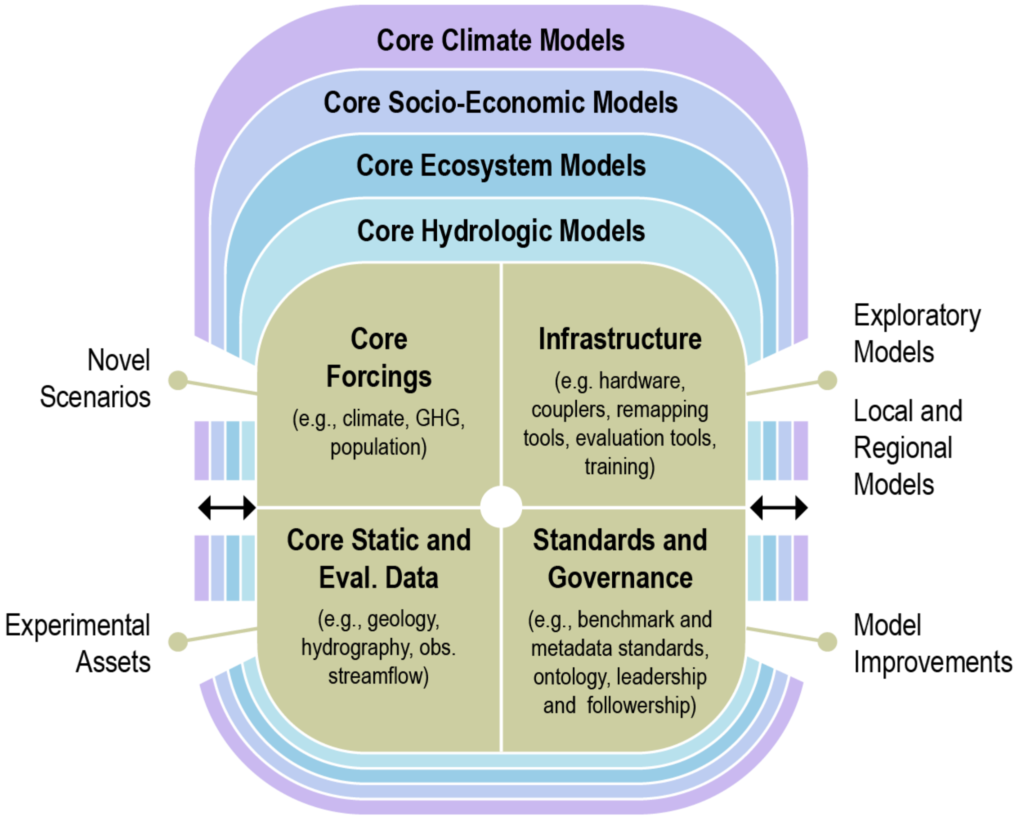

Figure B.1. Core components of the national testbed include forcings, infrastructure, data, and standards and governance. Key models for a national testbed include hydrologic, ecosystem, socioeconomic, and climate models (source: A. Dugger and the national testbed group).

B.1.3 Promoting R2O2R Innovations

The national testbed must overcome three barriers to encourage translational R2O2R innovations.

The first barrier is ensuring that all collaborative agencies and academic partners understand the purpose for the R2O2R translation. This requires that all parties have a clear and shared definition of the problem to be solved, goals, and outcomes. It is also crucial to engage stakeholders throughout the process. These issues must be addressed by investing in the creation of “user stories” to help ensure all necessary transition/operational partners are present from the beginning of a project and have a common vision for success. Furthermore, the national testbed should engage social scientists to better facilitate collaborations across agencies and stakeholder groups to create a “common language” and enhance interdisciplinary partnerships.

Next, there is a potential opportunity to leverage current resources that exist within individual agencies and minimize redundant efforts across agencies. This second barrier encompasses challenges to sharing resources and ideas across different government agencies. A proposed solution is to establish a broader working group for the IHTM national testbed that includes representation across all relevant agencies. This working group should also engage early career individuals within agencies and academia to build a diverse pipeline with a deep understanding of R2O2R. To break down this second barrier, there must be a commitment to sharing all components of modeling work across agencies, including metadata, datasets, compute requirements, and standards. There is an opportunity to learn from existing academic-federal partnership programs, like the NOAA Cooperative Institutes, to identify best practices around interagency resource and idea sharing.

The final barrier would then be the current lack of dedicated funding and resources for interagency collaboration within the IHTM framework.

B.1.4 Vision for the National Testbed

At its core, the national testbed should be a central organizing component of a formalized IHTM CoP that serves as a social-scientific-technical nexus at the national level. It should comprise an established interagency working group or task force that provides leadership to identify testbed priorities and resources (technical and human) for collaborative efforts within the testbed. The working group needs to have commitments from all relevant agencies, including USGCRP, DOE, EPA, NASA, NOAA, USACE, USBR, USDA, USGS, NSF, and U.S. Department of Homeland Security (including FEMA). The working group should help establish a platform and common conceptual frameworks for the free exchange of information and ideas. The national testbed, as an information service site, should be accessible by all agencies, where it provides software and data for model testing, input, and evaluation, along with human and technical support to maintain these resources. It should focus on national-level issues while developing strong synergies with the regional testbeds. For example, the suggested data platforms and benchmarking tools should consider modeling challenges for varied regions (e.g., climate, terrain, and land use). Efforts under the national testbed should encompass varying levels of complexities and utility for a wide range of users (e.g., undergraduate students to experienced researchers).

The IHTM national testbed has the potential to transform the status quo by embracing flexibility and accelerating discovery. First, the testbed should be intentional in its awareness that the people who contribute to and use it are critical components of the platform. This means that the testbed will provide a safe and inclusive environment for collaboration. As mentioned above, it will create a leadership structure that will be accountable for the success of the national testbed. To do so, it may draw on existing interagency working groups that are already in this space. The leadership team would be responsible for defining the “Grand Challenges,” sketching a roadmap for how goals will be accomplished and building incentives for continued leadership and followership. The national testbed will be transformative by allowing users to embrace an “entrepreneurial mindset,” encouraging users to prototype models and ideas quickly so that they can “fail fast and move on” to the next idea. Finally, it offers a first-of-its-kind, cross-agency “common operating picture” for hydrologic modeling that summarizes current status, evolving needs, and where resources are being leveraged. The national testbed offers the opportunity for the seamless movement of data across sources, scales, models, and users. The common operating picture would advance the status quo by allowing agencies to make better decisions about model and data use (“fit for purpose”) and where to prioritize new resources.

B.2 Mid-Atlantic Regional Testbed

Lead authors: Scott Steinschneider (Cornell University), Jared D. Smith (USGS), Jim Yoon (PNNL), Ning Sun (PNNL), Jeni Keisman (USGS)

B.2.1 Mid-Atlantic Region Potential IHTM Capabilities

IHTM capabilities developed to meet the challenges of the Mid-Atlantic region have the potential to advance hydrologic science in human-natural systems, with scalable benefits to similar regions across the nation. There are acute needs in the Mid-Atlantic to better understand how human systems, infrastructure, and water management impact the natural hydrologic cycle, and how those impacts feed back into human systems. Enhanced IHTM capabilities could advance our modeling and understanding of how to represent and manage the evolution of infrastructure, such as reservoirs, urban drainage networks, and green infrastructure, in response to the interplay between urban development and natural hazards, such as floods, droughts, and compound extreme events. For example, IHTM capabilities could improve our representation of the water quantity and quality benefits of local scale best management practices, which are a key pathway through which local and state entities make investments in improved water management and coastal resilience. In the Delaware River Basin, IHTM capabilities could help to resolve how reservoir operations can be used to manage emerging water quality threats (e.g., the need to push back the salt front in estuary systems during drought and as sea level rises), but also how these operations then impact the availability of water during other times of year for human and environmental water supply needs.

There is substantial uncertainty around the feed forward and feedback effects of these and other such human actions on water quantity and quality, and improvements in this area would make critical advances in the science of hydrologic prediction at the interface of natural and built environments. Such advances are critical to predicting and subsequently managing changing flood risk, water supply, and ecosystem challenges in heavily populated regions, which is a major concern throughout the nation.

B.2.2 Mid-Atlantic Region IHTM Capabilities for Interagency and Partner Collaboration

The Mid-Atlantic is one of the most populated regions in the country and one of the first to be developed; consequentially, it has some of the most comprehensive observational gaging networks for both water quantity and quality in the nation. In addition, these long observational records have been augmented by recent investments in next-generation monitoring capabilities, such as autonomous underwater vehicles to map water quality in estuary environments and floating sensors to track surface water-groundwater interactions. The densely populated region of the Mid-Atlantic has also attracted a diverse set of modeling efforts to represent hydrologic processes across urban, rural, and coastal environments. However, these data and models have been developed across multiple federal and state agencies, with limited coordination and organization across the range of capabilities already present. A Mid-Atlantic IHTM testbed could take advantage of existing engagement infrastructures through which these agencies already communicate, such as the USGCRP Coastal IHTM (which has evolved into the broader IHTM workstream), the NOAA Coastal Coupling Community of Practice, the Chesapeake Bay Program Partnership, and the NASA-led Chesapeake Bay Working Group, to better leverage resources to support IHTM capabilities that address shared needs.

A critical IHTM capability to enable collaboration across agencies and regional partners is to develop a coherent benchmarking system that could be used to better understand the degree to which existing models can accurately capture complex hydrologic behaviors at the human-natural interface. Core components of this benchmarking system would be a hub hosting data and model manifest that would enable partners to understand the data available to train and test models meant to represent core natural and human components of the hydrologic system, as well as models in existence today that can capture some of these behaviors. A benchmarking system would also provide a framework or set of standards for model and data development and sharing across agencies and partners, as well as a strategy by which regional partners could test how these models predict changes in hydrologic outcomes of interest in response to human system imprints on the landscape and river system. Ultimately, such a comprehensive benchmarking system for model intercomparison and sharing would help determine which models are fit-for-purpose in different applications, which would enable more cogent interactions between agencies and regional partners charged with tackling different emerging hydrologic challenges in the Mid-Atlantic region.

B.2.3 Promoting R2O2R Innovations

A Mid-Atlantic testbed for IHTM capabilities has a unique potential to promote innovations in R2O2R because there are already well-established R2O2R frameworks in the region. For example, in the Chesapeake Bay Watershed, there already exists a process by which scientific advances that resolve the impacts of local best management practices on water quality can be integrated into basin-wide modeling to estimate compliance with total maximum daily load requirements set for the Chesapeake Bay (see CAST – Home Page [chesapeakebay.net]). In the Delaware River Basin, the Delaware River Basin Commission and River Master help to guide research efforts toward operational implementation and to use operational challenges to help identify new research needs. A Mid-Atlantic testbed for IHTM capabilities can leverage these existing R2O2R channels to identify lessons already learned in terms of existing strengths and weaknesses, as well as how emerging IHTM capabilities can improve upon these processes (Figure B.2).

The dense population and decentralized management of water resources throughout the Mid-Atlantic region also provide a challenge and an opportunity to advance R2O2R innovations. As in other regions of the Northeast U.S., land and water resources are governed across multiple jurisdictions, with a heavy emphasis on "home rule" at the local (e.g., municipal, county) scale. Accordingly, there are many different actors with a direct role in decision-making or the ability to influence decision-making. A Mid-Atlantic testbed could help explore how best to advance IHTM capabilities to support decision-making in such a complex institutional context. For instance, such a testbed could leverage and advance a recent human systems typology canvass developed for multi-sector systems analysis,[1] mapping decision-making needs or services (e.g., governing versus provisioning, short-term versus medium-term versus long-term) to actors and actions in the system and determining how these actors and actions should be represented within a model given specific types of decision-support needs.

[1] Yoon, J., P. Romero-Lankao, Y. C. E. Yang, C. Klassert, N. Urban, K. Kaiser, K. Keller, B. Yarlagadda, N. Voisin, P. M. Reed, and R. Moss. 2022. "A Typology for Characterizing Human Action in MultiSector Dynamics Models." *Earth's Future* 10 (8): e2021EF002641. https://doi.org/10.1029/2021EF002641.

Figure B.2. The timescale on which research insights are generated operates independent of decision timescales. An adaptive, iterative R2O2R process allows insertion of new insights into operational decision-making frameworks as they emerge (source: J. Keisman).

B.2.4 Vision for a Mid-Atlantic IHTM Testbed

An IHTM testbed in the Mid-Atlantic could define a collaborative space and set of protocols to share the extensive datasets and modeling tools already developed throughout the region, as well as a system for comprehensive and structured inter-model comparisons to evaluate the fitness-of-purpose of these modeling tools at the human-natural system interface. The Mid-Atlantic is well-suited for testbed development given the readiness of existing modeling capabilities that could contribute to this shared space. An IHTM Mid-Atlantic testbed should build on existing regional integrated modeling activities, such as those in the Chesapeake Bay Watershed and Delaware River Basin, so that testbed activities can be designed around the lessons learned from those established initiatives. This testbed should help bring together a CoP for federal agencies working in the region, including the USGS, DOE, NOAA, and EPA, focused on critical topics of concern, such as water quality and flooding. Importantly, the testbed would help develop a shared conceptual framework for communicating and understanding the natural and human system and their interactions with the region. The region also benefits from a very actively engaged academic community, bringing additional opportunities to enhance collaborative resources (see for example Chesapeake Global Collaboratory | University of Maryland Center for Environmental Science [umces.edu]).

The envisioned IHTM testbed in the Mid-Atlantic region will transform the status quo of hydrologic modeling in human-natural systems in a way that can more directly enhance information production to support local and regional decision-making. The data and model density available in the Mid-Atlantic will allow this testbed to answer questions regarding the value of different types of data and different types of model integration activities to support emerging decision-making challenges in densely populated regions. Such insights could fundamentally advance our knowledge about the types of data and model investments that are needed to improve transferable scientific understanding of emerging challenges in human-natural systems that are less data and model rich.

B.3 Upper Colorado River Basin (UCRB) Regional Testbed

Lead authors: Alejandro Flores (Boise State University), John Hammond (USGS), Matt Miller (USGS), David Moulton (Los Alamos National Laboratory), Ben Ruddell (Northern Arizona University), Vince Tidwell (PNNL)

B.3.1 UCRB IHTM Potential Capabilities

IHTM capabilities in the UCRB present an opportunity for scientific advancement within the basin, with national benefits based on better understanding and representation of key components, including snow, evapotranspiration, groundwater, reservoir storage, and streamflow. Collaboration among existing regional testbeds operated by multiple agencies, including USGS Next-Generation Water Observing System, DOE East River, Surface-Atmosphere Integrated field Laboratory, and SPLASH, along with the installation of additional instrumentation, such as new snow stations and radar, enables the comprehensive measurements needed to calibrate and evaluate integrated models. Further, ongoing drought conditions and difficult water allocation decisions in the basin motivate enhanced understanding of the ways that multisector and multicomponent interactions affect basin-wide water availability. Overall, this integrated approach will lead to improved decision-making, ensuring a more resilient and sustainable water management system for the nation. Applications could include the following:

- Forecast-informed reservoir operations tied to improved representations of soil moisture, groundwater, snowpack, and evapotranspiration
- Better understanding of compounding risks during droughts and wildfires to manage water supply more effectively
- The development of integrated models to understand the interaction of electric power generation on water resources and vice versa to aid in optimizing operations
- Quantifying changes in headwater streams due to climate and land use changes.

B.3.2 UCRB IHTM Capabilities for Interagency and Partner Collaboration

There are ample opportunities for collaboration in the UCRB among the USBR, states, tribes, NOAA National Integrated Drought Information System, DOE, USGS, USDA-Forest Service, Bureau of Land Management, non-governmental organizations, and local water users. Given the interdependent complexity and compounding impacts among key hydrologic, ecosystem, and anthropogenic processes in the basin, there are several improvements in data availability and scientific process representation that could be realized by collaboration in a UCRB testbed:

- There is a need for better representation of groundwater flow in many Earth system models, especially during low flows in drought periods. Additional monitoring data capturing subsurface storage changes and contributions to streamflows would facilitate this representation.

- Improved access to information on water rights, river compacts, reservoir operational rules, and environmental flow requirements would facilitate collaboration; lack of access hinders comprehensive understanding.
- Current and potential future human decisions and controls on the system and, in particular, the hydrologic effects of those decisions need to be incorporated in modeling efforts.
- The economic and social effects of hydro-terrestrial processes are critical in guiding modeling experiments and in benchmarking efforts.
- Advancements in snowpack remote sensing, such as Airborne Snow Observatory, necessitate a robust assimilation architecture for mass and energy conservation, which is crucial for accurate forecasting.
- Precipitation forcings must be better estimated using advanced satellite, airborne, and ground-based remote sensing techniques.
- High-resolution, intense precipitation events, impacts of fire burns on hydrology, and translating hydrological variability into decision-relevant endpoints should be addressed.

B.3.3 Promoting R2O2R Innovations

Bridging the gap between research software and operational tools is a long-standing and important challenge heightened by the dramatic changes in environmental systems due to climate change and increasing human demand. Successfully moving capabilities from the research to operational setting, and back, requires a clear demonstration of a fit-for-purpose capability with the required robustness, predictive skill, and scaling in the model and implementation.

A UCRB testbed provides an ideal setting to address these challenges in translation of R2O2R innovation. Specifically, development of a CoP that engages stakeholders and researchers around a set of use cases within a testbed provides a constructive way to apply the research software and operational tools to the same problem at the same scale. Also, it provides an opportunity to evaluate assumptions about the data and models and address weaknesses in both. A UCRB-focused testbed has significant R2O2R potential given the following mix of necessary ingredients:

- Leverage existing stakeholder interaction to develop use cases that bring together natural and human-engineered systems in ways that drive toward a CoP.
- Build on advances in high-fidelity process-level models to broaden the array of impacts from climate change and human pressures that can be explored in the research stage of the pipeline and seek to inform operational innovations.
- Design the testbed, and underlying use cases, such that various representations of natural and human systems can be readily applied in both short-term forecasting and long-term projections.

B.3.4 Vision for the UCRB Region Testbed

A UCRB IHTM testbed might include the following elements in practice:

- <u>Operated</u> by a dedicated, expert modeling and software development staff member and <u>located</u> at a research center that is trusted by all agencies involved to operate independently and in service to the whole community’s interests.

- Early career pathways that fund and encourage young professionals to develop their careers in the modeling, cyberinfrastructure, data science, and research infrastructure fields, so the testbed cultivates the talent needed for the agencies to accomplish integrated modeling over the long term.
- Cyberinfrastructure that implements current best practices for open, containerized, reproducible, high-performance computing of development-stage and pre-operational stage modeling.
- Visualization and exploratory user interfaces that make the testbed's data and results accessible to both scientists and agency authorities.
- Public-facing educational materials communicating the testbed's work to the U.S. public and policymakers.
- Data repository and model publication forum that hosts and distributes the testbed's models and data, independent of the agency that produced or funded the production of those datasets.
- Incorporation of formal model benchmarking and intercomparison processes, so diverse models can be rigorously and transparently evaluated for both applied decision performance and scientific hypothesis testing purposes.
- Wrapping and/or emulation of agency models of record so that diverse agency models of record can be integrated and compared with alternative models.
- Mechanisms for funding and access to the testbed by independent researchers, so agency modeling can relate to diverse crowdsourced modeling efforts, accelerating innovation.

The shared collaborative space offered by the UCRB testbed has the potential to disrupt *status quo* management and operations of this complex river system in a variety of ways. More effective sharing of data, workflows, use cases, models, and more, would greatly improve the efficiency of researchers and agencies alike. Efficiencies would be realized as more time could be focused on addressing scientific and water management questions and less time on finding, compiling, and harmonizing data and/or developing modeling capabilities and workflows.

Community building aided by the UCRB testbed would also challenge the *status quo*. Specifically, the testbed would help establish and maintain relationships between the research and operations community. Synergies of community collaboration are also expected to result in accelerated development of new datasets, models, and other outputs. The community established by the testbed would naturally broaden participation in, access to, and awareness of emerging innovations. In the same way, adhering to open and reproducible science practices allows for expanded community contribution and impact.

Sharing assets, tools, and facilities through the testbed would help move UCRB operations beyond the *status quo*. Broader sharing will facilitate model benchmarking/comparison opportunities that may not be possible if an individual researcher or group were to develop data and models on their own. Expanded testing and benchmarking resources could also help demonstrate which models are appropriate for which scales and questions; that is, facilitate better identification of "fit for purpose" models and datasets.

B.4 Great Lakes Region (GLR) Testbed

Lead authors: Venkatesh Merwade (Purdue University), Rebecca Muenich (University of Arkansas), Ryan McGehee (Iowa State University), Nancy Barth (USGS), Joe Hughes (USGS), Scott Painter (ORNL)

B.4.1 GLR IHTM Potential Capabilities

The hydrologic nature of the GLR, including the complex interaction of the lakes and climate, tributaries and groundwater, and human impacts from a growing population, agriculture, and industry, position IHTM capabilities to help address regional issues and advance understanding of similar issues in other regions and on a national scale.

IHTM capabilities for GLR could address regional and local issues related to climate, hydrology, and human dimensions. Specifically, IHTM could provide improved hydroclimatic metrics of multi-decadal hydroclimatic variability and improve our understanding of seasonal and annual changes in low, mean, and high peak streamflow. Modeling capabilities could include high-resolution hydrologic models of the entire Great Lakes watershed that can be driven by a suite of downscaled climate scenarios and regional climate model outputs. A key component of these models will be a better representation of Great Lakes' energy and surface fluxes. IHTM capabilities for GLR would also include human dimensions models, including socioeconomic aspects, agricultural components, and power systems. Inclusion of agricultural components will enable simulation of nutrient and sediment sources and their transport.

Improved simulation and representation of nutrients and sediments is critical to understanding their roles in ecosystem degradation and harmful algal bloom toxicity. IHTM for GLR could also include lake models that simulate acidification, salinization, and their future level projections under different management scenarios. IHTM for GLR would also include simulation and apportionment of sectoral water demand projections considering transboundary aspects between multiple U.S. states and Canadian provinces.

B.4.2 GLR IHTM Capabilities for Interagency and Partner Collaboration

GLR already has existing cooperative entities and collaborations that provide support for water-related activities. These include the Great Lakes Water Quality Agreement (GLWQA; a bi-national policy agreement), Great Lakes Restoration Initiative (GLRI; funding for on-the-ground projects), Great Lakes Compact (governs water withdrawals), and the International Joint Commission (IJC; a bi-national body implementing transboundary water solutions). These have resulted in action plans for water management in GLR, including the Great Lakes Action Plan (from GLRI), Domestic Action Plans (from GLWQA), and the Great Lakes Science Strategy (from IJC Science Advisory Board).

Essential IHTM capabilities that will strengthen these collaborations will include the following:

- Sharing of high-resolution data and model results with common standards, formats, and metadata.
- Shared high-performance computing resources.
- Common model products and open-source tools for common workflows.
- Open-source workflows from datasets to outcomes.

The above digital capabilities cannot be fully exploited without the supporting physical and collaborative infrastructure, including the following:

- Shared scientific infrastructure, including analytical labs, vessels, autonomous systems, buoys, and observing systems.
- Collaborative field campaigns and boundary layer studies across different agencies.
- Development of shared research priorities and collaborative funding.
- Forums for states/provinces to share relevant drivers and societal questions.

B.4.3 Promoting R2O2R Innovations

The extensive stakeholder networks and existing bi-national policies and initiatives can be leveraged in a GLR IHTM testbed. A GLR IHTM testbed would encourage translational R2O2R by adopting an open science/FAIR approach in data and modeling efforts, collaborative initiatives with universities and agencies, and education/training on testbed models. Most agencies within GLR, and also in other testbeds, are driven by operations. IHTM can encourage R2O2R innovation by having capabilities that address current and future operational needs. Such an approach can help connect existing Great Lakes models with federal agency software, expand research areas, and provide a pathway for fundamental research.

A GLR testbed can also enable R2O2R innovation through implementation of reproducible workflows, shared computing infrastructure, and benchmarking tools for model integration. Collaborative development, real-time integration between data and models, and linkages with socioeconomic modeling are essential for R2O2R (Figure B.3). IHTM testbeds that include digital twins and objectives driven by operational needs of multiple agencies will lead to R2O2R innovations.

Figure B.3. R2O2R framework applications in the Great Lakes Regional testbed (source: R. Muenich and GLR testbed group).

B.4.4 Vision for the GLR Testbed

Workshop participants identified the need for leveraging existing GLR resources to advance a CoP for testbed development. This would involve identifying early adopters, mapping out stakeholder networks, creating a shared dictionary, and meeting annually. This group would help to advance a hierarchical testbed that has a shared collaboration workspace, shared data to facilitate model intercomparisons, common workflows, and co-developed scenarios and storylines, all leading to improved model interoperability and model intercomparisons in the GLR testbed.

Given the characteristics of the GLR testbed, there would be a strong focus on the dynamic climate in the region, including a significant lake modeling component. An IHTM capable of advancing understanding of the environmental issues facing the GLR would need to consider lake hydrodynamics; groundwater exports to the lakes; biogeochemistry within the lakes; the effects of the lakes on local climate, including under a changing climate; and the hydrology and nutrient and sediment exports from the contributing watersheds. Such capabilities would also need to consider the interaction and co-evolution of human and natural systems, including the effects of land-use/land-cover change, evolving agricultural management practices, and population dynamics. Many of the modeling component capabilities are available and being used by agencies to address their mission needs for the GLR, but as an uncoordinated collection of components, they fall well short of addressing the interactions and interdependencies of complex coupled systems in the GLR.

A consensus among the workshop participants found that modifying existing subsystem models to be interoperable and, thus, creating a comprehensive systems-level modeling capability is technically possible and a laudable goal but would require a large development effort. A more tractable goal for an IHTM testbed in the GLR would be to put in place processes and frameworks to facilitate inter-model comparisons, accelerate the development of shared workflow tools, disseminate research results, and support the development of a CoP. Central to a testbed capability would be a virtual collaboration workspace that could host shared data for model intercomparisons and act as a clearinghouse for synthesized datasets, models, model outputs, and workflow tools. A coordinating council would have the responsibility of designing model intercomparison activities, including, for example, the establishment of baseline data, common scenarios/storylines for projections, and generally establishing priorities for interagency collaborations.

The GLR is one of the testbed locales where interagency collaboration, and even bi-national collaboration, is already happening and can be leveraged to advance IHTM efforts. An IHTM testbed focused on the GLR would expand those existing collaborations, reduce remaining siloed efforts, and move the GLR scientific community toward a R2O2R framework. By facilitating a GLR testbed, linkages to more national IHTM efforts would be solidified, and learnings could more effectively translate to other testbed regions.

B.5 Mississippi/Gulf Coast (MGC) Testbed

Lead authors: Jodi L Ryder (USACE), Limei Ran (USDA Natural Resources Conservation Service [NRCS]), John M Johnston (EPA Office of Research and Development [ORD]), Mukesh Kumar (University of Alabama), Yongping Yuan (EPA ORD)

B.5.1 MGC IHTM Potential Capabilities

The MGC testbed offers the opportunity to bring together multi-disciplinary expertise to address numerous multiresolution, large-scale challenges associated with hydroclimatic risks, and its nexus with agriculture, energy, and waterway sectors, including

- Estimation of precipitation extremes (hurricanes and tropical storms, Arctic bombs) and their implications (flood and drought) from local to continental scale.
- Soil and erosion management, and a better understanding of sediment sources, pathways, and sinks.
- Nutrients from agricultural as well as urban runoff.
- Inland and coastal carbon-nutrient-agrochemical water quality, hypoxia, and harmful algal blooms (HABs).
- Legacy and emerging contaminants; stormwater and runoff management.
- Surface-groundwater interaction, groundwater depletion, and water policy.
- Impacts of land use and land cover change, development, and infrastructure.
- Sedimentation, subsidence, sea level rise, and salinity intrusion.
- Impacts of climate changes on agriculture, energy, and water sectors, including extreme weather events and Gulf Coast ecology.

In addition, the MGC region represents a convergence zone for resource management, water policy, environmental justice, and other pressing societal issues with complex interdependencies around the central issue of multi-objective resource management. Opportunities exist to build multi-sectoral perspectives around upland, riverine, and coastal infrastructure to optimize prioritization and planning, construction, maintenance, and operation across the basin.

B.5.2 MGC IHTM Capabilities to Enable Interagency and Partner Collaboration

The MGC is characterized by multiscale, interdependent systems, so solutions for the area require capability advances to represent and model critical processes at various scales (individual field to HUC levels) and across scales (small watershed to basin). As there has been a rich legacy of research conducted in various watersheds and basins within the MGC, including by USGS, NOAA, USDA, EPA, and NASA, there is a need to organize historical data, models, and findings over the MGC. At heart is the need for a public platform for community exchange of datasets, models, and advanced science. This platform requires a common (meta) data standard and a systematic catalog to organize contributions into searchable characteristics such as fluxes or states that are being studied/measured/modeled, model scale, resolution, area of interest, technology readiness levels (TRLs), funding type, and availability for collaborative development. The catalog is envisioned to advertise and generate grassroots connections between projects and to create accessible entry points for community engagement.

Critical capabilities that would better enable collaboration include:

- Data storage, sharing, and processing capabilities to facilitate curation and add-on connections between efforts. The data infrastructure must be nested and multi-scaled, representative of the hydrologic diversity in the basin. Allow for benchmarking of current models/data, thus identifying the current gaps and future opportunities for improvement, and enable comparison of parameters (e.g., precipitation, nutrients, and sediments) across temporal and spatial scales with attention on extremes.

- Identification of explicit pathways for interagency engagement, collaboration, and training as critical aspects of project reporting.
- Innovative funding mechanisms that sustain research through the R2O2R cycle are needed. These may include multi-year timelines, planned rollover between TRLs, increased funding for communication and tech transfer activities, and scheduled transitions between R&D and operational funding sources.
- Comprehensive water cycle monitoring (i.e., meteorology, surface water, groundwater, and water quality) network from field-and sub-basin- to basin-scale to bring together inter- and trans-disciplinary stakeholders.

B.5.3 Promoting R2O2R Innovations

The MGC testbed is a natural fit for R2O2R innovations because of the existing networks required to coordinate operations throughout the system. Several R2O2R CoPs exist around key issues, including flood control, transportation and navigation, agriculture, and energy that can be leveraged to generate research questions driven by scientific and societal challenges relevant to multiple agencies. In addition, a testbed infrastructure serves to enhance existing R2O2R pipelines by exposing baseline information, demonstration opportunities, and stakeholder feedback (Figure B.4). The inclusion of MGC operational and infrastructure data and scenarios could enable scientifically informed changes in long-term planning. Emphasizing R2O2R includes creating deliberate pathways for communication, community engagement, multi-sector collaboration, and training to develop common goals, datasets, and models, along with mechanisms for continued development cycles. The MGC testbed can also strengthen the R2O2R pipeline by demonstrating the payoff of sustained, multi-year funding and grants to encourage academic participation through transition and implementation of research findings.

Figure B.4. R2O2R cycle for the Mississippi/Gulf Coast testbed (source: J. Ryder and MGC Testbed Group).

The MGC testbed could influence modeling to effect change by promoting:

- Integration across domains (agricultural, wetland, riverine, atmosphere, anthroposphere, human system) to address multi-disciplinary questions and societal needs on water, and carbon-nutrient cycling, sediment-agrochemical yields, agricultural productivity, ecology, climate change mitigation, and adaptation.
- Awareness among multiple organizations and authorities about large-scale issues, such as HABs and hypoxia related to the “dead zone” in the Gulf of Mexico.

B.5.4 Vision for the MGC Testbed

The MGC testbed is envisioned as a loose federation of efforts with a strong backbone of communication to build an accessible network of agency, academic, and community parties working in the general field of MGC hydrology and hydrology-impacted subjects. The testbed is driven by tasks: code, functions, data, ensemble modeling, and model comparisons with goals to improve them. A collaborative and integrated paradigm should support a small staff to sustain the effort and curate the data, models, and resources as the testbed infrastructure design evolves from an online catalog of projects to a more formalized structure of resources.

Initially, the MGC testbed would leverage current collaborative monitoring and modeling activities in the MGC region, such as:

- EPA’s Mississippi River Restoration and Resiliency Strategy and USACE Mississippi River Restoration Program, universities, and other stakeholders (e.g., Mississippi River Collaborative) partnering on integrating non-floodplain wetlands for nutrient transport.
- USGS and DOE Urban Integrated Field Laboratory looking at urban hydrology in Southeast Texas.
- EPA/USDA/Texas A&M AgriLife/UNC-Chapel Hill: an Integrated Multi-Media Modeling System that integrates air, land, water, and coastal areas to investigate nitrogen source, fate, and transport has been developed. The modeling system includes the following components: (1) Community Multiscale Air Quality (CMAQ), (2) Weather Research and Forecasting Model (WRF), (3) Environmental Policy Integrated Climate (EPIC), (4) Soil and Water Assessment Tool (SWAT), and (5) Coastal Generalized Ecosystem Model (CGEM) (Figure B.5).
- USDA/Texas A&M AgriLife: National Agroecosystems Model (NAM) modeling platform from the field to 12- and 8-digit HUC watersheds and national scale.

These current projects would be used to establish key benchmark cases/studies at different scales and a framework for community use as a reference through a regular-repeating workshop process.

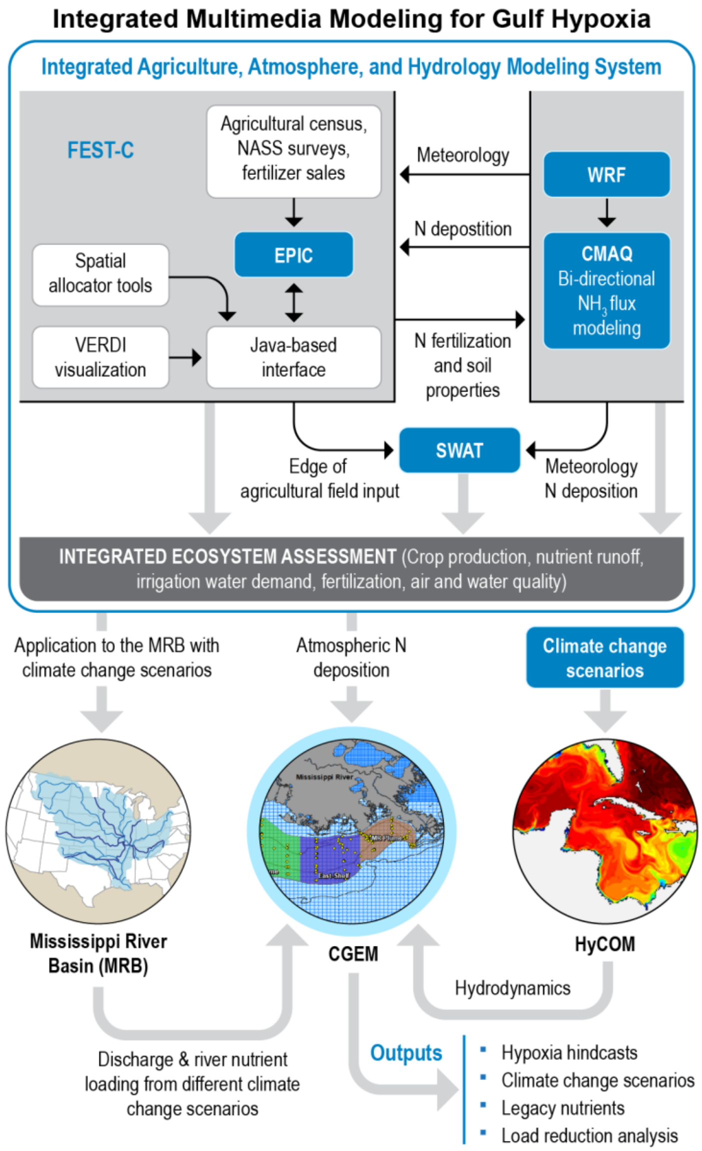

Figure B.5. An application of the Integrated Multimedia Modeling Framework for the Mississippi River Basin/Gulf Coast (source: Yuan et al., 2018;[1] Ran et al., 2019; Jarvis et al., 2024[2]).

The MGC testbed will embrace the idea that there can never be one single comprehensive hydrologic model for an area of such scale and diversity by creating a structure that values exchange, translation, and scaling to leverage research to greater effect than the sum of its

[1] Yuan, Y., R. Wang, E. Cooter, L. Ran, P. Daggupati, D. Yang, R. Srinivasan, and A. Jalowska. 2018. "Integrating Multi-Media Models to Assess Nitrogen Losses from the Mississippi River Basin to the Gulf of Mexico." *Biogeosciences* 15: 7059–7076. https://doi.org/10.5194/bg-15-7059-2018.

[2] Jarvis, B. M., J. C. Lehrter, L. Lowe, B. Penta, Y. Wan, M. Duvall, C. Simmons, W. Melendez, and D. S. Ko. 2024. "Coastal Generalized Ecosystem Model (CGEM) 1.0: Flexible Model Formulations for Simulating Complex Biogeochemical Processes in Aquatic Ecosystems." *Ecological Modelling* 496(C). https://doi.org/10.1016/j.ecolmodel.2024.110831.

parts. A platform for making models accessible and relevant to multiple agencies will transform the status quo from the siloed and duplicative efforts of the past. In addition, fostering a community of researchers across scales will help evaluate whether improved understanding of processes at smaller scales influences basin-scale predictions and operations, which, in turn, will help prioritize processes and mitigations that maximize impact at basin scale. Other capability advances that could be enhanced by an MGC testbed include:

- Facilitation of AI/ML model development alongside process-based modeling
- Evaluation and improvement of multiple coupled processes (e.g., atmosphere-N deposition-fertilization-nutrient losses, sediment/nutrient dynamics, salinity intrusion, flow extremes, impacts of agricultural management and practices)
- Benchmarking of current models/data, thus identifying the current gaps and future opportunities for improvement
- Facilitate understanding of human-water-soil-climate-atmosphere feedbacks and their influences on operations.

Ultimately, the MGC testbed offers a multiscale and geographically diverse region with complex implications for water, climate, and development outcomes to develop, test, and translate the IHTM modeling capabilities of the future.

Appendix C – Workshop Agenda

Integrated Hydro-Terrestrial Modeling 2.0 Workshop Agenda

Tuesday, October 31 – Thursday, November 2, 2023
ICF Conference Center | 1902 Reston Metro Plaza | Reston, Virgina 20190
Website: https://www.orau.gov/2023ihtm2 The passcode is *2023#IHTM**

Day 1: Tuesday, October 31, 2023		
Session A: Introductory Plenary		
8:30 – 8:45	Welcome and Overview. Vision, Challenges, and Opportunities: Agency Contexts and Perspectives	David Lesmes (USGS) on behalf of the Interagency Steering Committee
8:45 – 9:15	IHTM background building from 1.0 to 2.0	Pat Reed (Cornell U) and Katie Skalak (USGS) of behalf of the Scientific Organizing Committee
9:15 – 9:30	Workshop Agenda and Logistics	Yishen Li and Austin Scheetz (USGCRP/ICF)
Session B: Workshop Framing		
9:30 – 10:40 3 speakers, 17 mins each, with 5 mins for Q&A and transition Chair: Bob Vallario (DOE) Facilitator: Ying Fan (Rutgers)	National Testbed – Capabilities, Gaps and Needs • Leading edge research and science • User-inspired science and products • Research-to-operation-to-research (R2O2R) – Where does it fit in this life cycle? • Where are the opportunities? • What is working? What is not? • Cross-cutting agency capabilities (*e.g.*, CONUS404) • What are the unique agency needs and how do they guide our collaborative work?	**Speakers:** Paul Ullrich (LLNL per DOE) Jacob LaFontaine (USGS) Brenda Rashleigh (EPA)
10:40 – 11:00	**Break (20 min)**	
11:00 – 12:30 4 pairs of speakers, 20 mins for each testbed, with 10 mins for Q&A and conclusion Chair: Laura Lautz (NSF) Facilitator: Ying Fan (Rutgers)	4 Regional Testbeds – Capabilities, Gaps and Needs • Leading edge research and science • User-inspired science and products • R2O2R – Where does it fit in this life cycle? • Where are the opportunities? • What is working? What is not? • Cross-cutting agency capabilities (*e.g.*, CONUS404) • What are the unique agency needs and how do they guide our collaborative work?	**Speakers:** **Mid-Atlantic Region:** Hedeff Essaid (USGS) Ian Kraucunas (PNNL per DOE) **Upper Colorado River Basin:** Dave Gochis (NCAR) Rob Cifelli (NOAA) **Great Lakes Region:** Rob Hetland (PNNL per DOE) Debbie Lee (NOAA) **Gulf Coast/Mississippi Region:** Lauren Schmied (FEMA) John Johnston (EPA)
12:30 – 1:30	Lunch	

<table>
<tr><td colspan="3">Session C: Breakout Discussions – Desired Testbed Attributes</td></tr>
<tr><td>1:30 – 3:00</td><td>Desired Testbed Attributes – Capabilities, Gaps, and Needs

Charge Questions:
• What are some of the essential capabilities beneficial for the nation and for each region?
• For the nation and/or a given region, what are the common capabilities to enable interagency operation?
• What are the existing/emerging capabilities highly valued by individual agencies?
• What are the gaps/barriers in Earth System processes, data-implementation, workflow, and governance?

Discussion Template SharePoint Links
• U.S. National
• Mid-Atlantic
• Upper Colorado
• Great Lakes
• Gulf/Mississippi</td><td>Breakout Leads:
2 for each group (lead, notetaker)

National:
Laura Condon (U of AZ)
Aubrey Dugger (NCAR)

Mid-Atlantic Region:
Jeni Keisman (USGS)
Ning Sun (PNNL per DOE)

Upper Colorado River Basin:
Lejo Flores (Boise State U)
Ben Ruddell (Northern AZ U)

Great Lakes Region:
Venkatesh Merwade (Purdue U)
Becca Muenich (U of AR)

Gulf Coast/Mississippi Region:
Adam Schlosser (MIT)
Jodi Ryder (USACE)</td></tr>
<tr><td>3:00 – 3:20</td><td>Break (20 min)</td><td></td></tr>
<tr><td>3:20 – 5:00</td><td>Continuation of Breakouts before Break: Begin synthesis for report out on Day 2 morning
• Session leads can switch roles (lead/note taker)
• Breakout session leads will determine how to structure the afternoon session

Discussion Template SharePoint Links
• U.S. National
• Mid-Atlantic
• Upper Colorado
• Great Lakes
• Gulf/Mississippi</td><td>Breakout Leads:
Same as above</td></tr>
<tr><td>5:00</td><td>Adjourn</td><td></td></tr>
</table>

<table>
<tr><td colspan="3">Day 2: Wednesday, November 1, 2023</td></tr>
<tr><td colspan="3">Session D: Synthesis of Day 1 Activities</td></tr>
<tr><td>8:30 – 9:30

Facilitator:
Nathalie Voisin (PNNL)</td><td>Report out from each breakout groups on capabilities, gaps, and needs (following the template)</td><td>Breakout leads or designated reporter</td></tr>
</table>

Session E: Testbed Design – Framing Talks		
9:30 – 10:40 3 speakers, 17 mins each, with 5 mins for Q&A Chair: David Benson (NOAA) Facilitator: Ying Fan (Rutgers)	**The "What"** – Topical Themes, Major Challenges: • Hydro extremes – floods, droughts, wildfire, *etc.* • Water quantity, quality, use, sources, *etc.* • Human systems – uses and impacts, *etc.*	**Speakers:** **Hydro Extremes:** Ruby Leung (PNNL per DOE) **Water Quantity, Quality, Use, Sources:** Alison Appling (USGS) **Human Systems:** Nathalie Voisin (PNNL per DOE)
10:40 – 11:00	**Break (20 min)**	
11:00 – 12:30 (5 speakers, 15 mins each, with 15 mins for Q&A and panel discussion) Chair: Jared Entin (NASA) Facilitator: Ying Fan (Rutgers)	**The "How"** – Methodological Themes, Major Challenges • Computing environment, geospatial fabric, scenarios and forcings, coupling strategies, workflows, model evaluation and benchmarking • Open Science by Design • Scaling to become a truly community enterprise: communities of practice? • Translational research-to-operation-to-research (R2O2R) • Emerging technologies and methods (hybrid approaches, *etc.*) • Process and model integration, compounding events • Uncertainty, risk, and resilience • Temporal scales: short-term operations and long-term planning	**Speakers:** Chris Vernon (PNNL per DOE) – usability of science, open science, computing environment, workflows/coupling Roland Viger (USGS) – geospatial fabric, open development, R2O2R, benchmarking Martyn Clark (U Calgary) – benchmarking, community development, national scale, frameworks, UC/UQ Chrisopher Dunn (USACE) – R2O2R Jordan Read (CUAHSI) – Ecosystem of data and information services in a community of practice; interagency coordination; education and outreach workforce development
12:30 – 1:30	Lunch	
Session F: Testbed Design – Breakout Groups		
1:30 – 3:00	PART 1 Breakout Groups: 1 national + 4 regional à 5 total testbeds Discussion should cover "**what"** and "**how"**) Charge Questions: • What are the key hydrologic challenges that the testbed should consider? • What are the methodological capabilities, gaps, and needs that would enable collaborative advances in the testbed for IHTM (*e.g.*, open science by design)?	**Breakout Leads:** 2 for each group (lead, notetaker) **National:** Yadu Pokhrel (Mich State U) – "what" Tim Schneider (NCAR) – "what" Charlie Luce (USDA-FS) – "what" Roland Viger (USGS) – "how" Lauren Lowman (Wake Forest University) – "how" **Mid-Atlantic Region:** Pamela Sullivan (Oregon State) – "what" Jim Yoon (PNNL per DOE) – "what" Scott Steinschneider (Cornell U) – "How" Jared Smith (USGS) – "how"

	• How can the testbed aid in encouraging translational Research-to-Operations-to-Research innovations? Discussion Template SharePoint Links • U.S. National • Mid-Atlantic • Upper Colorado • Great Lakes • Gulf/Mississippi	**Upper Colorado River Basin:** Vincent Tidwell (PNNL per DOE) – "what" Matt Miller (USGS) – "what" Dave Moulton (LANL per DOE) – "how" John Hammond (USGS) – "how" **Great Lakes Region:** Nancy Barth (USGS) – "what" Ryan McGehee (Iowa State U) – "what" Scott Painter (ORNL per DOE) – "how" Joe Hughes (USGS) – "how" **Gulf Coast/Mississippi Region:** Ahmad Tavakoly (USACE) – "what" Limei Ran (USDA) – "what" Ethan Coon (ORNL per DOE) – "how" Mukesh Kumar (U AL) – "how"
3:00 – 3:20	**Break (20 min)**	
3:20 – 5:00	PART 2 Continuation of Breakouts before Break: Begin synthesis activities for report out on Day 3 morning (A template will be provided.) • Session leads can switch roles (lead/note taker) • Breakout session leads will determine how to structure the afternoon session. Charge Questions • What does the testbed look like, for the national and the 4 regions? • How will it fundamentally transform the status quo? • What are immediate actions and paths forward? • What are longer-term goals (3-year, 5-year)? Discussion Template SharePoint Links • U.S. National • Mid-Atlantic • Upper Colorado • Great Lakes • Gulf/Mississippi	**Breakout Leads:** (Same as above)
5:00	Adjourn	
5:00 – 9:00	Social networking event at the ICF Conference Center Sky Garden with soft drinks and refreshments	For in-person participants

Day 3: Thursday, Nov 2, 2023		
Session G: Synthesis of Day 2 Activities		
8:30 – 9:40	PART 3 Continuation of Day 2 Breakout • Focus on synthesis, arriving at testbed prototypes (core capabilities, configurations, *etc.*, addressing Day 1 gaps/needs); synthesis should be structured into "What" and "How" Discussion Template SharePoint Links • U.S. National • Mid-Atlantic • Upper Colorado • Great Lakes • Gulf/Mississippi	**Breakout Leads:** (Same as Session F)
9:40 – 10:00	**Break (20 min)**	
Session H: Report-out of Testbed Design Prototypes		
10:00 – 12:00 Facilitator: Katie Skalak (USGS)	Report-out from Day 2 – following the template.	**Breakout Leads:** (Same as above) And/or new leaders emerging from design breakout discussions
12:00 – 1:00	**Lunch**	
1:00	Adjourn for general participants	
1:00 – 3:00	Meeting of breakout leads, SOC, and ISC for outlining synthesis report and assigning author teams	**Leads:** ISC and SOC, breakout session leads, and emerging leaders
3:00 – 3:20	**Break (20 min)**	
3:20 – 5:00	Remaining business	

Appendix D – Workshop Participants

First Name	Last Name	Affiliation
Adam	Schlosser	Massachusetts Institute of Technology
Adnan	Rajib	University of Texas at Arlington
Aiden	Layer	ORISE
Albert	Kettner	CSDMS, University of Colorado
Alejandro	Flores	Boise State University
Alison	Appling	USGS
Andrew	Jones	Lawrence Berkeley National Laboratory
Andrew	Wood	NCAR; Colorado School of Mines
Ariel	Miara	National Renewable Energy Laboratory
Aubrey	Dugger	NCAR
Benjamin	Ruddell	Northern Arizona University
Bob	Vallario	DOE Office of Science
Brenda	Rashleigh	EPA Office of Research and Development
Brian	Clark	USGS
Brian	Cosgrove	NOAA NWS Office of Water Prediction
Casey	Burleyson	Pacific Northwest National Laboratory
Charles	Lane	EPA Office of Research and Development
Charles	Luce	USDA Forest Service
Charles	Scaife	DOE EERE
Charuleka	Varadharajan	Lawrence Berkeley National Lab
Chris	Frans	USBR
Chris	Lowry	NSF
Chris	Massey	USACE Engineers Research and Development Center
Chris	Vernon	Pacific Northwest National Laboratory
Christopher	Dunn	USACE Hydrologic Engineering Center IWR
Corinne	Bowers	USGS
Dave	Goodrich	USDA ARS Southwest Watershed Research Center
David	Benson	NOAA
David	Blodgett	USGS
David	Judi	Pacific Northwest National Laboratory

First Name	Last Name	Affiliation
David	Lesmes	USGS
David	Moulton	Los Alamos National Laboratory
David	Rosa	FEMA
David	Smith	EPA
David	Tarboton	Utah Water Research Laboratory, Utah State University
Debbie	Lee	NOAA Great Lakes Environmental Research Laboratory
Devendra	Amatya	USDA Forest Service
Dipankar	Dwivedi	Lawrence Berkeley National Laboratory
Douglas	Schuster	NCAR/UCAR
Drew	Loney	USBR
Eddy	Langendoen	USDA ARS
Elena	Shevliakova	NOAA GFDL
Emile	Elias	USDA Southwest Climate Hub
Erin	Towler	NOAA
Ethan	Coon	Oak Ridge National Laboratory
Fadji	Maina	NASA GSFC
Fred	Lipschultz	USGCRP
Gabriel	Senay	USGS
Gabriele	Villarini	Princeton University
Gary	Rowe	USGS
Geoff	Plumlee	USGS
Gil	Bohrer	DOE ESS
Graeme	Aggett	Lynker Technologies
Gregory	Characklis	University of North Carolina at Chapel Hill
Hailan	Wang	NOAA Climate Prediction Center
Heather	Golden	EPA Office of Research and Development
Hedeff	Essaid	U.S. Geological Survey
Hendratta	Ali	NSF
Holly	Holt	ORISE
Huilin	Gao	Texas A&M University
Ian	Kraucunas	Pacific Northwest National Laboratory
Isaya	Kisekka	University of California Davis

First Name	Last Name	Affiliation
Jacob	LaFontaine	USGS
Jacob	Zwart	USGS
James	Pauer	EPA Office of Research and Development
Jared	Entin	NASA
Jared	Smith	USGS
Jason	Roth	USDA NRCS
Jeff	Arnold	USDA ARS
Jeni	Keisman	USGS
Jennie	Rice	Pacific Northwest National Laboratory
Jennifer	Morris	Massachusetts Institute of Technology
Jeremy	Giovando	USACE
Jesse	Dickinson	USGS
Jim	Yoon	Pacific Northwest National Laboratory
Jodi	Ryder	USACE Engineer Research and Development Center
Joel	Corona	EPA
John	Brakebill	USGS
John	Bursi	DOE Water Power Technologies Office
John	Hammond	USGS
John	Johnston	EPA
Jordan	Read	CUAHSI
Joseph	Hughes	USGS
Jud	Harvey	USGS
Julia	Szinai	Lawrence Berkeley National Laboratory
Julie	Hewitt	EPA Water Economics Center
Katherine	Skalak	USGS
Katie	Flahive	EPA
Kevin	Low	NOAA NWS Missouri Basin River Forecast Center
Kristen	Swedberg	ORISE at EPA
L. Ruby	Leung	Pacific Northwest National Laboratory
Laura	Condon	University of Arizona
Laura	Lautz	NSF
Lauren	Lowman	Wake Forest University

First Name	Last Name	Affiliation
Lauren	Schmied	FEMA
Leila	Farhadi	George Washington University
Limei	Ran	USDA NRCS
Marci	Savoy	ORISE
Mark	Wigmosta	Pacific Northwest National Laboratory
Martyn	Clark	University of Calgary
Matt	Miller	USGS
Michael	Fienen	USGS
Michelle	Newcomer	Lawrence Berkeley National Laboratory
Mike	Johnson	Lynker, NOAA-Affiliate
Mimi	Hughes	NOAA Physical Sciences Laboratory
Mindi	Dalton	USGS
Mukesh	Kumar	University of Alabama
Nancy A.	Barth	USGS
Natalia	Travis	ORISE
Nathalie	Voisin	Pacific Northwest National Laboratory
Nels	Frazier	Lynker, NOAA-Affiliate
Nicole	Jackson	Sandia National Laboratories
Ning	Sun	Pacific Northwest National Laboratory
Noemi	Vergopolan	Princeton University/NOAA Geophysical Fluid Dynamics Laboratory
Pamela	Sullivan	Oregon State University
Patrick	Reed	Cornell University
Paul	Bayer	DOE Biological and Environmental Research program
Paul	Ullrich	Lawrence Livermore National Laboratory
Peter	McCarthy	USGS
Pin	Shuai	Utah State University
Raghavan	Srinivasan	Texas A&M University
Rajbir	Parmar	EPA
Raleigh	Martin	NSF
Rebecca	Muenich	University of Arkansas
Reed	Maxwell	Princeton University
Renu	Joseph	DOE

First Name	Last Name	Affiliation
Richard	Lammers	University of New Hampshire
Rob	Cifelli	NOAA Physical Sciences Laboratory
Rob	Hetland	Pacific Northwest National Laboratory
Roger	Gorke	EPA Office of Water
Roland	Viger	USGS
Ryan	Cabell	NCAR
Ryan	McGehee	Iowa State University
Samantha	Basile	USGCRP/ICF
Santosh	Ghimire	EPA
Scott	Painter	Oak Ridge National Laboratory
Scott	Peckham	University of Colorado, Boulder
Scott	Steinschneider	Cornell University
Sean	Kimbrel	USBR
shad	O'NEEL	USACE Cold Regions Lab (CRREL)
Shelly	Thawley	EPA
Shih-Chieh	Kao	Oak Ridge National Laboratory
Sonia	Isotov	ORISE
Stacey	Archfield	USGS
Terry	Nipp	Texas A&M University
Thomas	Wild	Pacific Northwest National Laboratory
Tim	Scheibe	Pacific Northwest National Laboratory
Timothy	Schneider	NCAR
Tom	Wall	EPA Office of Water
Venkatesh	Merwade	Purdue University
Vincent	Tidwell	Pacific Northwest National Laboratory
Virginia	Rynk	USACE
William	Collins	University of California, Berkeley; Lawrence Berkeley National Laboratory
William	Lehman	USACE
Xingyuan	Chen	Pacific Northwest National Laboratory
Xujing	Davis	DOE
Yadu	Pokhrel	Michigan State University

First Name	Last Name	Affiliation
Ying	Fan	Rutgers University
Yishen	Li	USGCRP
Yongping	Yuan	EPA
Zion	Clarke	DOE

Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

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