Community Advisory Committee for Water Prediction (CAC-WP)
Inaugural Meeting Findings and Recommendations

April 18, 2018

Community Advisory Committee for Water Prediction (CAC-WP)
Inaugural Meeting Findings and Recommendations

April 18, 2018

Table of Contents

Community Advisory Committee for Water Prediction (CAC-WP) Inaugural Meeting Findings and Recommendations

April 18, 2018

1. Introduction

The purpose of this report is to provide findings and recommendations of the Community Advisory Committee for Water Prediction (CAC-WP) to the National Weather Service Office of Water Prediction (OWP), an office within the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce. Note that recommendations are from individual CAC-WP members and do not represent a consensus of the panel, nor do they represent a comprehensive review of the OWP program. They are, rather, a subset of activities reviewed in Q2 FY2018.

The mission of the OWP is to collaboratively research, develop, and deliver state-of-the-science national hydrologic analyses, forecast information, data, decision-support services and guidance to support and inform essential emergency services and water management decisions. Looking forward, the OWP is poised to launch an historic transformation and modernization of hydrology and water prediction services within NOAA's National Weather Service. The OWP will play a critical role in enhancing water-related products and decision-support services across the country in support of the strategic objective of building a Weather Ready Nation. The OWP provides an unprecedented opportunity to improve federal coordination and collaboration in the water sector to address 21st century water resource challenges, such as water security, analysis, and prediction of hydrologic extremes.

The University Corporation for Atmospheric Research (UCAR) established and manages the CAC-WP. The purpose of the CAC-WP is to conduct a thorough independent review of OWP's water modeling capabilities, with emphasis on the National Water Model (NWM), other modeling innovations, and related data and information services. To address the growing needs of water resources stakeholders and the associated science and service gaps, this committee brings independent expertise and perspectives from across the community to provide recommendations to improve OWP's water modeling capabilities and related data and information services. The committee is tasked to consider the various activities OWP has already undertaken to address the requirements and associated gaps described in this report. This newly formed committee is comprised primarily of hydrologists, civil engineers, and other water resources science and data science experts and is administratively managed by UCAR. The CAC-WP members are water resources stakeholders external to NOAA, representing four sectors: Federal, Non-Governmental Organizations (NGO), Academia, and Private Sector. Reviews and recommendations from the CAC-WP are those of the committee and not of UCAR. The committee meets and produces a written report at least annually.

The CAC-WP met January 30 – February 1, 2018, at the National Water Center in Tuscaloosa, Alabama. The committee received briefings from NWS and other personnel on the following topics:

- Overview of the NWS Office of Water Prediction – Context, Vision, Goals;
- Overview of National Water Model Implementation;
- Concept of Impact-Based Decision Support Services;
- Overview of current NWM operational and developmental computational environments, planned enhancements, and anticipated needs.

The committee conducted a suite of discussions focused on aspects of these topics:

- Conceptual discussion on what Impact-based Decision Support Services (IDSS) for water resources products and services could/should look like in 5-10 years, in evolving the National Water Center and National Water Model, pertaining to federal, academia, and private sectors.
- Discussion on model development needed to attain IDSS goals, focusing on improvements to representation of physical and anthropogenic processes, and on optimizing use of physiographic data sets such as terrain data, stream networks, land use and land cover data, soils data, reservoir characteristics, and other relevant data sets.
- Discussion on optimizing use of in situ and remotely-sensed observations for data assimilation and model validation.
- Discussion on establishment of a community developmental testbed and associated governance, focused on what is needed from federal, academic, and private sector perspectives; identification of successful models/examples; and the role of standards (e.g., Earth System Modeling Framework) in enabling community development.
- Discussion of how operational, development, and community testbed computational environments could/should evolve to address multiple objectives.

Based on these discussion, committee members were tasked to provide recommendations to the OWP and were asked to limit their recommendations to topics that had been discussed.

2. Committee Recommendations

2.1 Federal Sector

2.1.1 Matthew Farthing

Research Hydraulic Engineer
Coastal & Hydraulics Laboratory
Engineering Research and Development Center (ERDC)
U.S. Army Corps of Engineers
Matthew.W.Farthing at erdc.dren.mil

Recommendations

There are several short-to-medium term feature additions and enhancements identified in the multi-year strategic science and services plan that are of high priority to ERDC efforts:

- Representation of reservoirs/control structures in channel routing;
- Improved bathymetry representations;
- Coupling with coastal and estuarine models;
- Better representations of infiltration and surface water/groundwater coupling, particularly in hyper-resolution nested models.

These are areas we are actively working on in collaboration with the NWM community or are well-positioned to address in the near future.

Nested/hyper-resolution modeling will be key to many of the NWM strategic goals. However, the process fidelity, data requirements, and computational performance needed to achieve "hyper-local" resolution may require a different paradigm. Consider "pushing the models to the data." That is, there needs to be support for spinning up local models quickly and tying them directly to local data streams. This is where techniques like machine learning and model reduction could help build responsive models for real-time situational awareness. Assimilation of these data will need to occur locally first before propagating back to the national-scale model. The key to modularity is well-defined interfaces. The way the interfaces are enforced (governance) will be more critical than the actual software technology that is used. However, I think it's important to continue to engage the broader scientific computing community to leverage their expertise and resources. In particular, the DOE has a long experience with component-based architectures and sustained scientific computing support.

I would err on the side of ensuring the core software is well-described behind solid interfaces with clear integration points over feature addition.

Try setting up a test problem and integration exercise where at least two groups integrate an external module (or nested hyper-resolution model) as part of a feature request to evaluate NWM design and modularity.

Biography

Dr. Farthing began work at the Coastal and Hydraulics Laboratory in 2007. Prior to that he served as a research assistant professor in the Environmental Sciences and Engineering department at the University of North Carolina. His research interests include computational modeling of multiphase flow and transport phenomena and scientific computing in Python and C++. Most of his current work focuses on hydrodynamic modeling in data-sparse regions. In particular, his current research and development efforts include finite element methods for multiphase flow and transport, reduced order modeling for free-surface hydrodynamics, and bathymetry estimation in riverine and littoral environments.

2.1.2 David Lesmes

Program Manager
Office of Biological and Environmental Research
Subsurface Biogeochemical Research (SBR) Program
U.S. Department of Energy
David.Lesmes at science.doe.gov

Recommendations

Motivation: 21st Century Science

- Grand scientific challenges are complex, multi-scale, and push the frontiers of every discipline they touch.
- Impacts on society, energy security, and our everyday lives bring a sense of urgency to this mission.
- Data is growing exponentially, and computational power is pushing towards the exa-scale: everything seems possible.
- Interdisciplinary community-based approaches that are flexible, extensible and agile offer a powerful approach.

Vision vs. Reality

- Vision: Software ecosystems to meet the science challenges should:
  - be agile and adaptable through modular designs with components that are interoperable, composable, flexible, and extensible;
  - be community driven, leveraging interdisciplinary teams, and promoting innovation;
  - support rapid prototyping of new capabilities;
  - be open source, accessible, using agile development methodologies and continuous integration testing;
  - be sustainable in life-cycle, supporting reproducibility.
- Reality: Many applications fall short in some (or even all) of these requirements.

Challenges for the Broader Hydrological and Terrestrial Modeling Communities

- Legacy multiphysics applications were developed assuming that all cases could be enumerated, a priori (i.e., efficient but fragile).
- Hardware/software is changing rapidly:
  - code must be designed for constant refactoring;
  - programming models are uncertain/unknown.
- Best practices (e.g., agile methodologies) are maturing but are not used uniformly across teams or communities.
- The scientific "business model" lacks recognition of the critical role that software engineering plays, and its true cost.
- Developers/scientists need to maintain their autonomy and brand.

- Licensing is challenging, paperwork can be slow and overwhelming.
- Interdisciplinary teams struggle with communication (language and approach), and trust.
- Governance of the community, and its ecosystems is needed.
- Components need to be plugged into something—a framework(s):
    - It is likely that modeling frameworks will continue to evolve, and that different groups/agencies will prefer to use different modeling frameworks.
    - Is it possible to define standards for the development of modeling components that would allow those components to be used in a variety of modeling frameworks (perhaps with slight modification)?

Building a Shared Modeling Ecosystem

- WHY: To accelerate scientific productivity by leveraging synergies to advance the missions of our agencies and communities to do better together what may be difficult or even impossible to do alone.
- HOW: A phased approach to advancing a modeling ecosystem:
    - Must develop a long-term vision (design attributes) that is informed by broad community deliberation involving both domain and computational experts.
    - Agencies take the lead in helping communities to define standards/methodologies/protocols that enable coordination, collaboration and competition in an open ecosystem that facilitates innovation:
        - A key step will be engagement, and when necessary, establishment of technical working groups that can define and publish community standards for all aspects of the ecosystem (data, interfaces for model components, math libraries, etc.);
        - Establishment of community standards enables the independent development of interoperable components and capabilities.
    - Encourage and enable the use of modern software engineering methodologies (e.g., software productivity and improvement plans; Better Scientific Software website: https://bssw.io/).
    - Build trust and incentives: establish sustainable niches in the ecosystem.
    - Develop hybrid management structures bridging networks and hierarchies:
        - *"Large organizations move with the speed and agility of small teams", which have (1) trust; (2) common purpose; (3) shared consciousness; (4) empowered execution – decentralized decisions and autonomy.*
          Gen. Stanley McChrystal, Team of Teams
- WHAT: A shared modeling ecosystem, consisting of a flat repository of components, which is built using modern software engineering principles and a sustainable system of governance, can become an extensible platform (or resource) which can be flexibly used by federal agencies, the academic community, and the private sector and to which they can continue to share their developments:
    - Hydrological Modeling Capability:

        - water quantity
        - water quality
    - Terrestrial Modeling Capability,
    - Agricultural Modeling Capability,
    - Modeling of Coupled Natural-Human Systems,
    - etc.

Specific recommendations:

- Libraries:
    - Trajectory is towards the increased use of libraries in community code development.
    - NOAA should engage the broader technical community (HPC experts) to evolve their computational strategy to enable the wider use of libraries in their operational codes.
        - This will decrease the amount of new code that needs to be written.
        - If the libraries are continually refactored by computational scientists to optimize performance and portability, then the application code will be less likely to be disrupted by evolving computational architectures.
- Modularity:
    - Trajectory is towards increased granularity of modeling components and associated data structures.
    - NOAA should engage the technical community to develop a process for establishing requirements for interfaces to enable interoperability of components (similar to protocols for the development of standards for interfacing on the internet).
- Testbeds:
    - Need to engage community to develop scenarios, metrics, benchmarks, classes of common problems to rigorously evaluate the performance of models and modeling components.
    - Need to facilitate the hierarchical testing of components and codes and the sharing of results with reproducible workflows.
        - This will facilitate the rigorous comparison of different modeling approaches and the evaluation of trade-offs in terms of model fidelity, predictive skill and performance.
- Broader engagement of DOE Technical Community:
    - DOE HPC expertise and resources;
    - DOE Field Research Sites and interdisciplinary research teams;
    - Explore possibility of developing interagency collaboration on ExaScale model development.

Biography

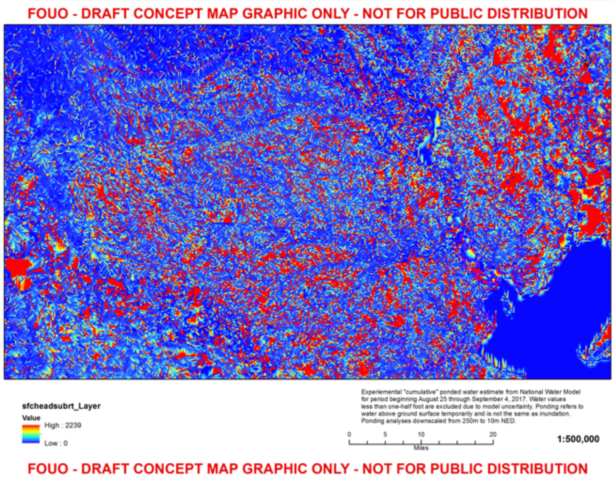
David Lesmes manages the Subsurface Biogeochemical Research (SBR) program in the Climate and Environmental Sciences Division in the Department of Energy's Office of Biological and Environmental Research. The overarching objective of the SBR program is to advance a robust, predictive understanding of how watersheds function as integrated hydro-biogeochemical systems and how these systems respond to perturbations as needed to address U.S. energy and environmental challenges. David's technical area of expertise is hydrogeophysics and before coming to the DOE he worked as an Assistant Professor at Boston College and as a Postdoctoral Fellow at the Massachusetts Institute of Technology. He received his PhD in Geophysics from Texas A&M University and a B.A. in Physics from the University of California at San Diego. David has served on many interagency committees including the OSTP Subcommittee on Water Quality and Availability (SWAQ), the U.S. Group on Earth Observations (USGEO), and the U.S. Global Change Research Program (USGCRP) Integrated Water Cycle Working Group.

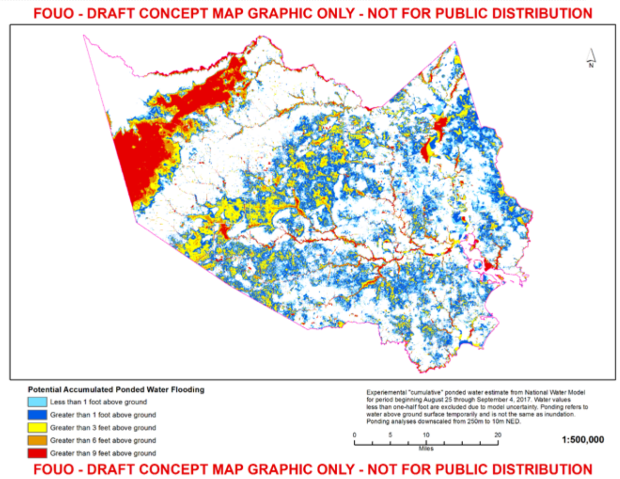
2.1.3 Gene Longenecker

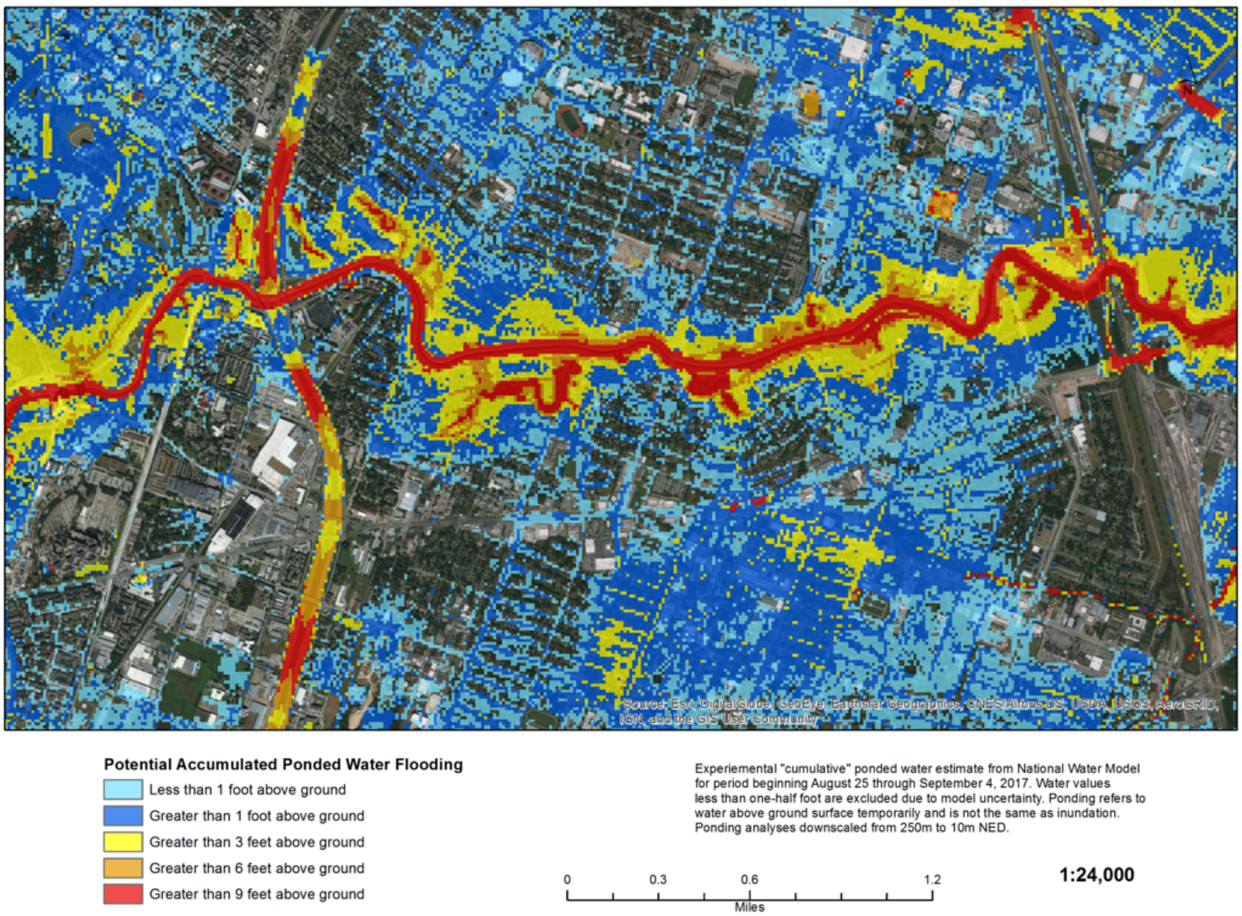
Senior Physical Scientist
Planning & Exercise Division, Response Geospatial Office
Federal Emergency Management Agency (FEMA)
Herbert.Longenecker at fema.dhs.gov

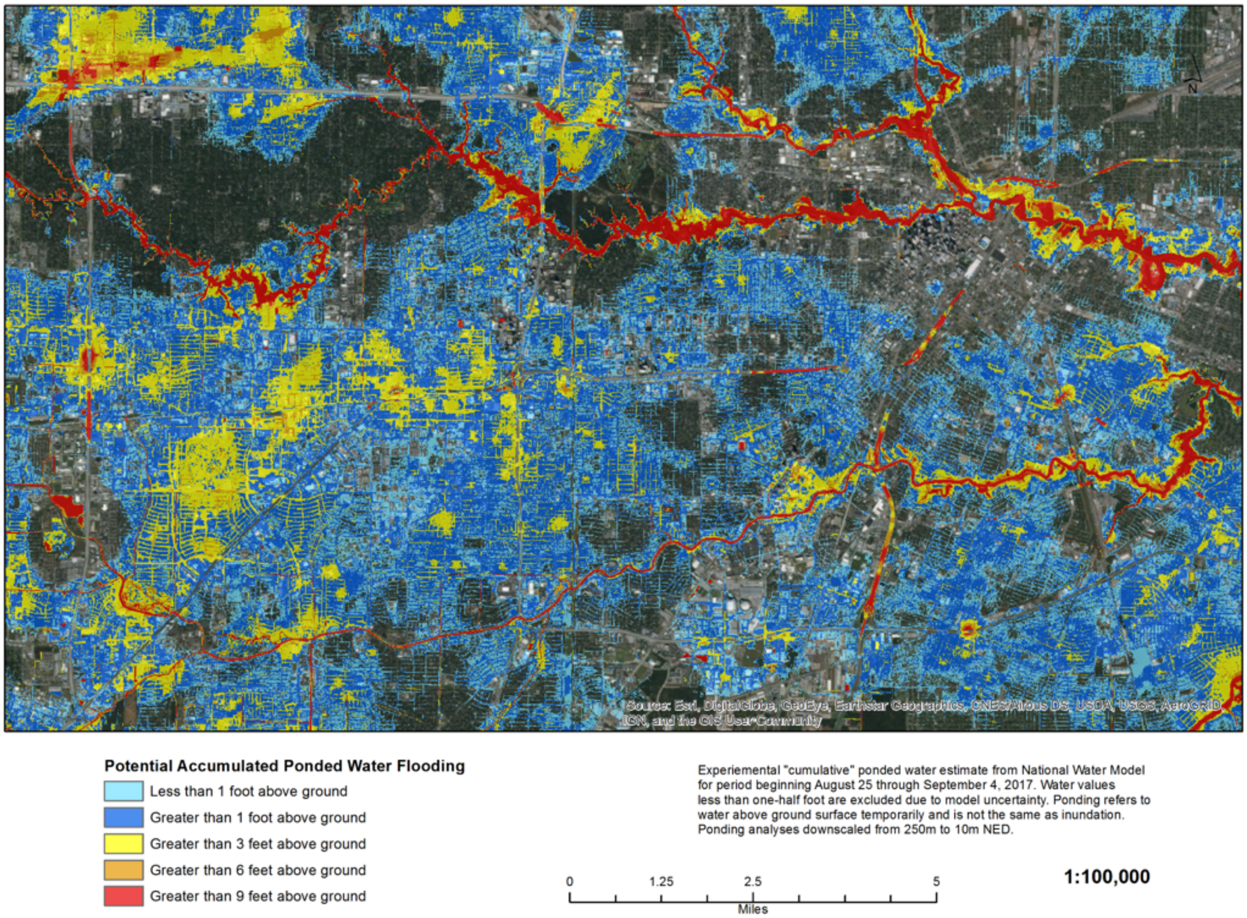
Thoughts on Downscaling NWM/WRF-Hydro

- Going from WRF-Hydro to 10-meter Flood Extents and Depth-Damage Estimation: Cumulative Hurricane Harvey Ponding (Surface Head) Forecast Data.
- David Maidment to Gene Longenecker during Harvey: "Help translate the NWM data."
- Per Joe Nimmich's point - Using data that currently exist:
    - Downscale surface head data from 250-meter WRF-H resolution to 10-meter USGS NED DEM.
    - GIS data conversion for possible inland/urban/river "flood inundation graphic" similar to the NHC storm surge inundation graphic.
- From surface head (ponding) to depth grid.

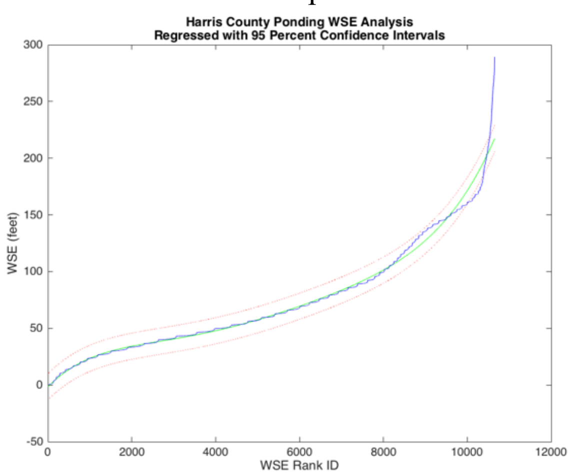

FOUO - DRAFT CONCEPT MAP GRAPHIC ONLY - NOT FOR PUBLIC DISTRIBUTION
sfcheadsubrt_Layer
Value
High : 2239
Low : 0
Experiemental "cumulative" ponded water estimate from National Water Model for period beginning August 25 through September 4, 2017. Water values less than one-half foot are excluded due to model uncertainty. Ponding refers to water above ground surface temporarily and is not the same as inundation. Ponding analyses downscaled from 250m to 10m NED.
0 5 10 20
Miles
1:500,000
FOUO - DRAFT CONCEPT MAP GRAPHIC ONLY - NOT FOR PUBLIC DISTRIBUTION

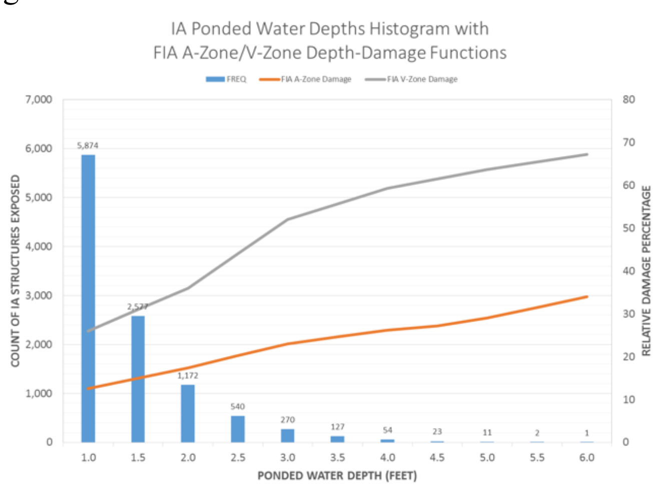

FOUO - DRAFT CONCEPT MAP GRAPHIC ONLY - NOT FOR PUBLIC DISTRIBUTION
Potential Accumulated Ponded Water Flooding
Less than 1 foot above ground
Greater than 1 foot above ground
Greater than 3 feet above ground
Greater than 6 feet above ground
Greater than 9 feet above ground
Experiemental "cumulative" ponded water estimate from National Water Model for period beginning August 25 through September 4, 2017. Water values less than one-half foot are excluded due to model uncertainty. Ponding refers to water above ground surface temporarily and is not the same as inundation. Ponding analyses downscaled from 250m to 10m NED.
0 5 10 20
Miles
1:500,000
FOUO - DRAFT CONCEPT MAP GRAPHIC ONLY - NOT FOR PUBLIC DISTRIBUTION


Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Potential Accumulated Ponded Water Flooding
Less than 1 foot above ground
Greater than 1 foot above ground
Greater than 3 feet above ground
Greater than 6 feet above ground
Greater than 9 feet above ground
Experiemental "cumulative" ponded water estimate from National Water Model for period beginning August 25 through September 4, 2017. Water values less than one-half foot are excluded due to model uncertainty. Ponding refers to water above ground surface temporarily and is not the same as inundation. Ponding analyses downscaled from 250m to 10m NED.
0 0.3 0.6 1.2
Miles
1:24,000

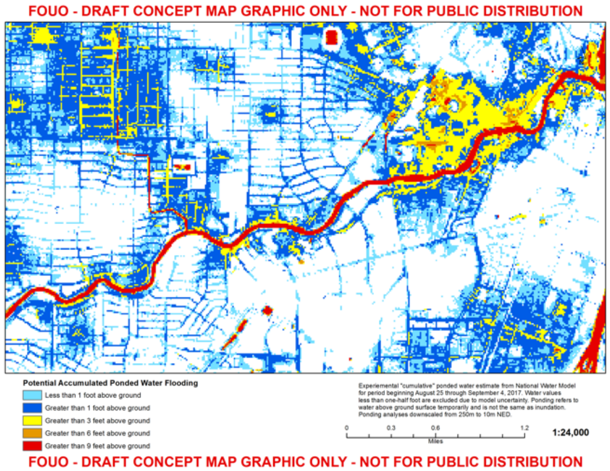


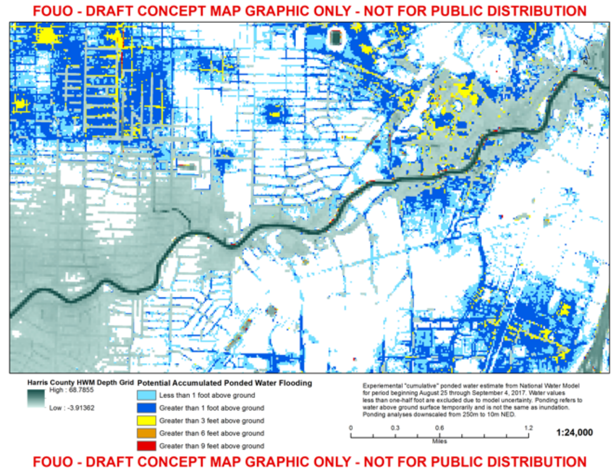
- From forecast depths to forecast damages





- 10m Ponding depths vs. HWM depths (1:24k)





NWM Ponding Depth Grid IA Comparison

- NWM ponding statistical best fit model:
  - 158,040 IA points intersected out of 335,115.
  - About 47.2% intersected/exposed to cumulative ponding flood extent.
- NWM ponding statistical best fit model + 1 delta error:
  - 277,704 IA points intersected out of 335,115.
  - About 82.7% intersected/exposed to cumulative ponding flood extent.
- Evaluations to-do:
  - Revisit with most recent IA data and HWM from inspections.
  - Compare with lidar HWM flood extents and depth grids – excellent agreement with preliminary HWM flood depths/extents.

Biography

H. E. "Gene" Longenecker, III is a Senior Physical Scientist and modeling lead for the Response Geospatial Office in the FEMA Headquarters Planning & Exercise Division. Gene is a team lead and coordinator for FEMA's Modeling Task Force (MOTF) and Storm Surge/Data Manager for the Hurricane Liaison Team (HLT); he previously served as FEMA Region IV's Earthquake/Hazus Program Manager and Regional Geospatial Coordinator. He is responsible for interagency modeling and data coordination, perishable data collection missions driving disaster impact analytics, and development of multi-hazard risk and vulnerability assessment methodologies for federal and state emergency response planning and program activities. He serves as a lead subject matter expert in risk, vulnerability, loss estimation, GIS, and remote sensing on behalf of FEMA during federal disaster response operations.

Gene has bachelor's degrees in Geography and Philosophy (B.S) and a Master of Arts degree in Geography (M.A.). He is also affiliated with the University of Colorado at Boulder's Geography Department and Center for Science & Technology Policy Research, where he studies flood risk, economic development, and sustainability while finishing his doctoral degree in Geography (Ph.D., expected 2018). He has organized and conducted numerous domestic and international training, technical, and conference workshop sessions on behalf of FEMA, emphasizing the applications of GIS, modeling, data analyses, techniques development, and general geographic and scientific principles supporting disaster management.

2.1.4 Glenn Moglen

Research Hydrologist
Agricultural Research Service
U.S. Department of Agriculture
Glenn.Moglen at ars.usda.gov

Recommendations

- Keep low flows in mind (Function 1b):
    - Background: The majority of our discussions have focused on floods. Low flows/drought flow are a concern for water supply, navigation, irrigation.
    - Recommendation: Keep USDA-ARS in mind as a possible purveyor of high quality soil moisture (e.g. SMAP) and evapotranspiration (ET) information (e.g. ALEXI) that can inform both low flows and flood flows.

Biography

Glenn Moglen is a research hydrologist at the Agricultural Research Service in Beltsville, Maryland where he is the head of the Hydrology and Remote Sensing Laboratory. He is formerly a professor of Civil and Environmental Engineering at both the University of Maryland and Virginia Tech. Dr. Moglen earned his BS from the University of Maryland, his MS from Colorado State University, and his PhD from the Massachusetts Institute of Technology. He is also a registered professional engineer. Dr. Moglen's research focuses on the hydrologic modeling of land use and climate change. He is an officer and active member of several technical committees with the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE). Dr. Moglen is the author of a recent textbook on open channel flow.

2.1.5 Jonathan Nelson

Research Hydrologist
Water Mission Area
U.S. Geological Survey

Recommendations

- SERVE the results asap (!) 24-year record and forecasts (CUAHSI?).
- SEPARATE communities that (1) serve data, (2) provide modules, and (3) use the output – much easier to address.
- REMEMBER, almost all the high priority items that your constituents want depend on channel bathymetry.
- Draw a line and focus on short term objectives with maximum emphasis on data assimilation and demonstrated SKILL in discharge prediction. The rest will take care of itself.

Biography

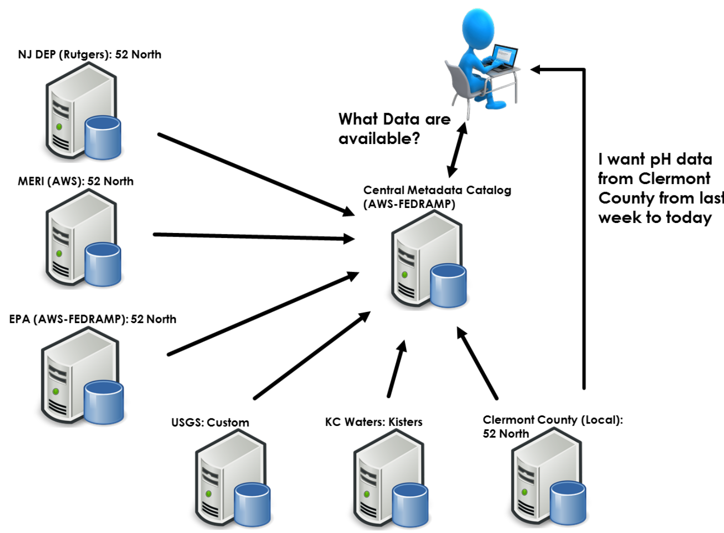
Jonathan Nelson received his Ph.D. in Geophysics from the University of Washington. His research work focuses on flow, sediment transport, and morphodynamics in rivers, with particular emphasis on the mechanics of bars and bedforms. He is currently Chief of the Environmental Fluid Dynamics Project and the Geomorphology and Sediment Transport Laboratory (GSTL) in Golden, Colorado. In addition to carrying out basic and applied research on rivers, his group at GSTL develops, distributes, and provides education for multidimensional modeling codes for river applications.

2.1.6 Dwane Young

Chief, Water Data Integration Branch
Office of Water
Environmental Protection Agency (EPA)
Young.Dwane at epa.gov

Recommendations

- Promote a Common Data Infrastructure:
  - Work with the community to adopt standard approaches for sharing time-series data.
    - Use a central catalog/search index (CUAHSI) that references every data owner's assets with the corresponding metadata for each sensor.
    - Allow for quick searching and discovery of available data.
    - This approach is similar to how Google allows you to search the internet.
    - Use Open Standards and develop metadata standards.
    - To support modeling, you may need an archiving/aggregation component.



- Develop a Governance Structure:
    - Critical components of a governance structure include:
        - Senior leaders set strategic direction.
        - Managers and Resource managers identify areas of focus, set policies, adopt standards, and direct resources to core tools.
        - Technical Workgroup certifies new components as being consistent with the standards or network and develops technical recommendations.
        - Resources to fund core tools and to fund innovations that are in line with areas of focus or strategic direction.
- Engage the Private Sector:
    - EPA has had some success in engaging the private sector in Air Quality monitoring and communication. For example, Google has been very interested in having access to Air Quality data to serve that back to the public in innovative ways and to incorporate that with other data.
    - The private sector can serve as a host for large federal data sets (must be a copy and not the 'official source').
    - They can also bring significant data analytical capabilities to the table in developing secondary products.
- NHDPlus 3.0 Decision Points:
    - Not a recommendation to the NWS per se, but we need a decision framework for determining whether or not to invest in NHDPlus 3.0 versus waiting for NHDPlus Hi-Res.
    - There will likely continue to be a need for a medium resolution NHDPlus product, but can that be derived from a Hi-Res NHDPlus, and what would be the schedule for having that available?

Biography

Dwane has worked with EPA since 2005 and has worked on environmental data management systems in both the Office of Water and the Office of Solid Waste and Emergency Response. Dwane has also served as the Federal Liaison to the Western States Water Council. Dwane led the initial development of the Water Quality Exchange (WQX) for EPA, played a key role in the development of EPA's Clean Water Act Integrated Reporting systems, oversaw the implementation of updates to the RCRAInfo system, and has extensive experience with assisting partners in sharing water quality data. Dwane has a degree in Fisheries and Wildlife Management from Utah State University. He has spent the last seventeen years working on environmental data management systems.

2.1.7 Don Cline (CAC-WP Co-Chair)

Associate Director for Water Resources
U.S. Geological Survey (USGS)
Dcline at usgs.gov

Recommendations

- Conceptual discussion on what water resources IDSS products and services could/should look like in 5-10 years, in the context of evolving the National Water Center and National Water Model, as pertains to federal, academia, and private sectors.
- Discussion on model development needed to attain IDSS goals, focusing on improvements to representation of physical and anthropogenic processes, and on optimizing use of physiographic data sets such as terrain data, stream networks, land use and land cover data, soils data, reservoir characteristics, and other relevant data sets.
- Discussion on optimizing use of in situ and remotely sensed observations for data assimilation and model validation.
- Discussion on establishment of a community developmental testbed and associated governance, focused on what is needed from federal, academic, and private sector perspectives; identification of successful models/examples; and the role of standards (e.g. Earth System Modeling Framework) in enabling community development.
- Discussion of how operational, development, and community testbed computational environments could/should evolve to address multiple objectives.
- Future of water resources IDSS products and services:
  - The OWP should consider a two-pronged approach to supporting IDSS, with equal emphasis:
    - First, it is important to provide "universal" IDSS to some level of detail, so that everyone, anywhere, can access and benefit from OWP water prediction information.
      - This likely takes the form of web-delivered interactive maps, graphs, forecast discussions, etc., much like NWS does today.

        - Second, because there are likely tens of thousands (if not more) specific IDSS applications for water prediction information, and there is no feasible way for a federal agency to be aware of, account for, or support all of these in a meaningful way, it is important to broadly provide the OWP water prediction information in the most open, accessible ways possible.
            - This includes both model output products such as analyses and forecasts, and relevant modeling tools and supporting data sets to permit myriad IDSS "clients" to tailor the information to their application.
                - First priority should be getting the data "out there" as widely as possible.
                - Second priority should be providing interpretive tools, post-processing applications, and other tools to facilitate the use and application of OWP information.

- Model Development to Attain IDSS Goals:
    - Modularization and standardization of the modeling code architecture should be a very high priority.
        - The objective of this should be (at least) two-fold:
            - Enable flexibility to support the variety of IDSS applications that may emerge in response to NWM products and services.
                - In the context of the above two-pronged approach, while OWP cannot anticipate every IDSS application, some common denominators may emerge that should be quickly incorporated into the universal products produced by the OWP. Flexibility to do this rapidly will be paramount to maintaining widespread interest in the products, and this isn't feasible until the code is well-modularized.
            - Enable broad community contributions to the modeling capacity.
                - There is a much broader base of specialists who can contribute improvements to process representations, use of specific data sets, etc., than the relatively small cohort that is able to work effectively on a large monolithic code base. Community engagement will occur more rapidly with modularized codes.
    - Although our discussions focused on IDSS in the flooding arena, NOAA's strategic interests in water resources prediction go beyond that into areas such as drought and water quality. The first instantiation of the NWP was focused on representing high flows and flood peaks, at some expense to other objectives. To achieve its broader objectives, the OWP should consider a major development effort focused on developing strong, fundamental predictive capability for low-flow conditions (e.g. incorporation of shallow groundwater and baseflow) and for advanced hydraulic flow and constituent transport.

        - These two capabilities are heavy lifts and will likely require a broad community effort. They should probably not be viewed as incremental upgrades to the current model framework, and perhaps should instead be thought of more as next-generation capabilities.
            - These require substantial advancements in data (e.g. soils and channel bathymetry) as well as process algorithms and computational requirements.

- Optimizing Use of Observations:
    - Unlike its meteorological counterpart within the NWS, the OWP is not deeply involved in collection of water observations and relies instead on partners (mainly USGS for streamflow observations). Currently, a major limitation of the OWP modeling, data assimilation, and validation efforts is the vastly disproportional relationship between 2.7 million stream reaches being predicted, and the roughly 8200 stream gauges being used for assimilation and validation.
        - The OWP should take steps to identify what an optimized streamflow dataset should look like. There are thousands more streamflow observations collected across the landscape, with varying quality, accessibility, and latency. One approach could be "as many as possible", but that is likely to be problematic for a variety of reasons. Requirements for an optimized "network of networks" is needed before meaningful steps can be taken to harness additional streamflow observations.
    - In the northern and northeastern U.S., snowmelt flooding in spring is a major problem that the OWP should be able to help address. In the western U.S., snow packs are key to understanding water supply and the potential for drought. The NWS has already made considerable effort to access and systematize a wide array of snow observations across the country through SNODAS. A near-term priority for the OWP should be to take steps to incorporate these data into the NWM via data assimilation.
        - It should not be assumed that current SNODAS gridded products are appropriate for assimilation into the NWM. SNODAS was developed in 2002, and the best methods used then may not be the best now. A study should be undertaken to evaluate the efficacy of the snow models underpinning both SNODAS and the NWM, the data assimilation (DA) approach used in SNODAS and the DA tools available through the NWM, and the characteristics of snow observations available today.
            - In other words, resist the temptation to simply lift and shift a 16-year old capability into the NWM.
    - As noted above with respect to streamflow observations, the NWM is generally under-constrained. Identifying and understanding sources of error in the model are essential to improve predictions, and this requires a more comprehensive use of available observations that can shed light on the quality of model states and fluxes.

        - The OWC should consider strategies to substantially increase the use of a wide variety of available observations to understand and improve model performance.
            - As noted above, more observations of streamflow are available, as are a substantive suite of snowpack observations (including snow-covered area from satellites, and in situ snow depth and snow water equivalent), as well as numerous in situ soil moisture observations. Ingestion and use of these readily available data should be a high priority, as they provide direct insights into the storage and flux components of the model.
            - Current remotely sensed land cover information may provide rapid insights into areas where the model may be underperforming due to land cover changes since the static land cover version used in the NWM. A simple comparison between the two data sets may be all that is needed to determine areas that may be invalid in the model.
                - Looking forward, a study should be conducted to evaluate the utility of incorporating newly available high-resolution dynamic land cover data sets derived from Landsat within the NWM prediction framework.
            - A significant weakness in the hydrologic observing system is evapotranspiration (ET). The OWP should consider conducting a study focusing on the role of ET in the water balance of the NWM to determine the importance of strengthening the ET observing system (which would likely be a community effort and not necessarily the burden of the OWP). Understanding the magnitude of ET in the overall water budget, and its spatial and temporal variability, are paramount to developing requirements and building the business case for an enhanced ET observing system.
- Community Developmental Testbed and Associated Governance:
    - Other recommendations here have noted the importance of getting the model code out to the community sooner rather than later. The window of interest and opportunity can be narrow—if the community perceives you're unwilling to share the code, they will move on to other things since they have no means of contributing.
        - The OWP should make the NWM code publicly available as quickly as possible, regardless of its condition (e.g. level of documentation, clarity, modularity, etc.). As these conditions improve, keep releasing newer versions.
            - There will be a period of time—perhaps several months to a year—when those who are interested will simply explore the code, think about what they can offer, and informally communicate with the OWP. During this period, it's not critical to have established

governance mechanisms and frameworks for incorporating new improvements, just a willingness to converse with the community. But that period will soon end, and those things will be necessary.

- With consideration of the research-to-operations (R2O) and operations-to-research (O2R) "funnel":
  - A capability analogous to the Developmental Testbed Center (DTC) is needed for advancement of numerical water prediction:
    - This capability should:
      - Serve as a middle ground, an interface between the "atomic" world of basic research and development, and the highly systematic and constrained world of operational prediction;
      - Host the latest operational version of the NWM code (and other relevant model codes) for the community to access and develop (aka the "sandbox");
      - Establish common standards and interoperable architectures that enable community modeling to flourish;
      - Provide a suite of test cases and standards for the community to achieve in order to incorporate their developments into future code versions;
      - Conduct testing of new developmental versions of model codes;
      - Provide governance over the testbed process;
      - Provide a convenient (not necessarily sole) source for the OWP to select new model improvements for NWM version upgrades.
    - This capability should not:
      - Prevent researchers at the atomic level from interacting with the operational environment if that is where their interests lie; and vice versa.
    - The DTC for water prediction should include, at a minimum, a coalition of NOAA, USGS, DOE, and NSF.

- Evolution of Computational Environments
  - Upon formulation of the DTC coalition, it should develop a strategy for supplying the computational environment needed for function of the DTC.
    - "Computational environment" should be considered broadly to include not only the hardware end of high-performance computing, but network bandwidth to facilitate transfer of large modeling data sets, storage for short- and long-term needs, and computational science necessary to foster strong and effective hardware and software systems.
    - The DTC formulation should strive to supply appropriate systems to support current architectures, as well as look forward to evolution of

future systems. The DTC should aim to ensure that long-lead computational architectural changes are recognized, tested and supported in advance of when they are needed.

- The academic computational science community should be engaged more directly in development of modeling and IDSS capabilities to ensure that the best possible science is integrated within the water prediction enterprise.
- The OWP and its partners (possibly the envisioned Water DTC and CUAHSI) should consider formulating a "center for advanced computational hydrology", or some similar concept, to foster rapid growth and capability development in this arena. Hydrologic science is generally lagging behind other fields in this regard, and future advancement of NWM-class models will require more expertise in development and application of advanced computational methods to efficiently solve complex problems.

Biography

Dr. Don Cline is the U.S. Geological Survey's Associate Director for Water Resources. Don leads USGS research, monitoring, assessment, modeling, and prediction of the nation's water resources. The USGS Water Resources Mission Area (WMA) provides society with the information it needs on water quantity and quality across the Nation. Don oversees the WMA's efforts to advance understanding of the controls over water availability; to better predict changes in water quantity and quality in response to natural and human-induced changes; to anticipate and respond to water-related emergencies and conflicts; and to deliver timely water data, analyses, and decision-support tools seamlessly across the Nation to support water-resource decisions.

Don joined USGS in 2016 following a 19-year career with the National Oceanic and Atmospheric Administration's National Weather Service, where he served as the Director of the National Water Center, the Chief of the Hydrology Laboratory, and the Director of the National Operational Hydrologic Remote Sensing Center. Don has been in the Senior Executive Service since 2010.

Don has over 20 years of research, development, and operational implementation experience in applied and basic hydrologic and cryospheric science, large-scale field experiments, integrated environmental modeling, development and application of airborne and spaceborne observing systems, and applications of geographic information systems.

Don holds a Ph.D., M.S. and B.S. from the Department of Geography at the University of Colorado, Boulder.

2.2 Non-Governmental Organizations

2.2.1 Ehab Meselhe

Vice President for Engineering
The Water Institute of the Gulf
emeselhe@thewaterinstitute.org

Recommendations

- Coding Philosophy:
    - Once an official version of the NWM is established, it can be released to the research community.
    - Developments from the research community can provide significant improvements to the NWM.
    - Establish an internal team to evaluate and if worthy, assimilate these new developments and improvements into the NWM.
    - Establish a standard (thorough and comprehensive) set of tests to examine the performance of new versions before accepting it as the new official version.
- Update/maintenance:
    - Establish an update strategy so that the model stays dated with new:
        - Topo-bathy surveys
        - Control structures/reservoirs/ etc.
- Channel Routing Component of the NWM: identify modeling approaches that
    - do not compromise the models' computational efficiency;
    - do not cause computational failures.
    - improve (at least incrementally) the accuracy of the predictions especially in regions where channels play a significant role in the flood elevations and extent.
- Long term goal: Establish the NWM to be the backbone to drive local high/hyper resolution flood models used to establish/create the FEMA maps. That would provide a consistent platform at the national level—that would be a great service to the community.
- If/when you establish a NWM community, don't limit the participation to "scientists." Here is my quote: "Believing that science has all the answers, and contributions from locals are not needed, leads to poor buy-in the tools being offered."

Biography

Ehab Meselhe, Ph.D., P.E., is the vice president for engineering at the Water Institute of the Gulf, and a Professor at the River-Coast Science and Engineering, Tulane University. He has more than 20 years of experience researching wetland hydrology, sediment transport, and computer modeling of inland watersheds, coastal wetland, estuarine, and riverine systems. Dr. Meselhe served as Louisiana's technical lead for the Mississippi River Hydrodynamic and Delta

Management Study and helped build the numerical models that provided a foundation for Louisiana's 2017 Coastal Master Plan. He also served as an Associate Editor of the Journal of Hydrology (Elsevier), and the Journal of Hydraulic Research (International Association of Hydraulic Research).

2.3 Academia

2.3.1 Ana Barros

Professor of Civil and Environmental Engineering
Duke University, Pratt School of Engineering
barros at duke.edu

Recommendations

- First Order:
  - Long View—A framework for adaptation, innovation and evolving demand:
    - technology
    - science
    - society
  - Handling Success—intellectual and technological agility.
  - Handling Failure—accountability, responsibility, forensics.
  - Services—community.
- Proposals for Working Groups—recommend forming working groups on:
  - Precipitation
  - Surface-subsurface interactions including riverways
  - Metrics
  - Multiscale hydraulics
  - Water prediction
    - Hydroinformatics
    - Infrastructure and urban systems
    - Monitoring risk and rapid response
  - Seasonal to decadal variability (groundwater and drought)
  - Wetlands, coastal hydrology and hydraulics
- Discussion led to recommendation that these groups should be formed and maintained through CUAHSI, not NWC.

Biography

Dr. Ana P. Barros is the James L. Meriam Professor of Civil and Environmental Engineering in the Pratt School of Engineering at Duke University, and a Professor of Earth and Ocean Sciences faculty of the Nicholas School of the Environment. Dr. Barros' research is on multiscale water cycle processes with a special focus on hydrometeorology and hydrology of mountainous regions. Her research approach relies strongly on observational process studies *using remote sensing and ground-based observations, coupled modeling across the atmosphere and terrestrial continuum, and integration of models and observations. Dr. Barros has served and continues to serve in numerous committees and boards of various federal agencies, the NRC, and various professional and scientific societies. Dr. Barros is a Fellow of the AAAS, AGU, AMS and ASCE.*

2.3.2 Clint Dawson

Professor, Department Associate Chair
Head of Computational Hydraulics Group
John J. McKetta Centennial Energy Chair in Engineering
Department of Aerospace Engineering and Engineering Mechanics
University of Texas, Austin
Clint at ices.utexas.edu

Thoughts, Questions and Recommendations

- What are the measures of success for the NWM? Who are the major stakeholders? What are short and long-term goals?
- There are many opportunities for R2O and O2R involving multi-disciplinary collaboration between the domain scientists, computational scientists, computer scientists, data scientists, etc. to improve the long-term viability of the NWM. I believe this is necessary for training students and postdocs who would eventually be employees of the NWC. How would these efforts be funded? Can NSF or other agencies be persuaded to participate in special funding efforts to enhance the NWM?
- Pick a few representative watersheds or rivers and use them as testbeds to test model and data fidelity, accuracy vs. robustness, etc. For example, the San Jacinto River during Hurricane Harvey would be a good testbed.
- Learn from best practices in software engineering, data and code reuse, etc. from other communities that have demonstrated some success at maintaining a community code. However, the NWM is extremely complex and may require new paradigms.
- As you provide operational data to emergency managers, they will always want more, and being able to meet those needs may be the key to success or failure.

Biography

Dr. Dawson's research focuses on numerical methods for partial differential equations, specifically flow and transport problems in computational fluid dynamics (CFD); scientific computing and parallel computing; finite element analysis, discontinuous Galerkin methods; shallow water systems, hurricane storm surge modeling, rainfall-induced flooding; ground water systems, flow in porous media, geochemistry; data assimilation, parameter estimation, uncertainty and error estimation.

2.3.3 Richard Hooper

Research Professor
Tufts University
Dept. of Civil and Environmental Engineering
Water Resources Group
Richard.Hooper at tufts.edu

Recommendations

- Provide rough roadmap to communicate to academic researchers where development is heading so that they can understand where NWM is heading.
- Advertise NWM output more widely :
  - How will academics learn about NWM?
  - Need longer archive of NWM output than the current 48 hours of rolling data on NOMADS.
  - The current effort by RENCI/Hydroshare to extend forecasts to keep a 30-day rolling window and archiving assimilation data is laudable, but ad hoc and may not be sustainable. There needs to be a plan developed, possibly in consultation with CUAHSI (and NSF).
  - The relative utility of different forecasts and the assimilation run is not clear and must be explored more fully. The NCAR retrospective is likely of interest to a wide audience and should be released. The effort to preserve NWM output for Harvey is a potential model that should be evaluated.
  - The roles of NCAR, CUAHSI, and NCEI need to be determined and communicated to the research community.
  - Relative value of analysis/assimilation runs, forecasts, selective storms (e.g., Harvey archive).
- Use Cases for engaging community-defined data and tool requirements. Consider these different classes of users when making decisions about what NWM output to archive:
  - Output users.
  - Model users.
  - Model developers.
- Using crowd-sourced data to augment NWM validation/assimilation:
  - Potential Summer institute project,
  - Georeferenced photos of inundation,
  - Translation of photo into data for assimilation.

Biography

Dr. Richard P. Hooper is currently a Research Professor at Tufts University in the Water Resources group of the Department of Civil and Environmental Engineering. He was the founding Executive Director of CUAHSI which he led from 2003 to 2017. While at CUAHSI, he oversaw the creation of the CUAHSI Hydrologic Information System and the founding of the Water Data Center, the first NSF-supported community facility for hydrology. Dr. Hooper *worked with the Office of Hydrologic Prediction to develop and to execute the National Water Center's Innovators Program Summer Institute. Dr. Hooper is active in catchment research, having been elected Chair of the upcoming Gordon Research Conference on Catchment Science and chairing the External Advisory Board for the Helmholtz Center's Terrestrial Environmental Observatory Network.*

2.3.4 Kyle Mandli

Assistant Professor
Department of Applied Physics and Applied Mathematics
Columbia Data Science Institute
kyle.mandli at columbia.edu

Recommendations

- One key objective for the OWP with respect to the NWM should be to establish an open governance model that catalyzes and grows a community that consists of all available stakeholders with interests in the development of the NWM. This includes governmental, non-governmental, academics (through CUAHSI), and the private sector. Suggestions:
    - Create a committee that would consist of some representation from all stakeholders listed above that would steer development and incorporation of features.
    - Create a procedure for community proposals that would enhance the NWM/WRF-hydro model. Suggested places to look for models are the Python Enhancement Proposals (PEPs) and other similar open source projects.
- Overall development of the NWM and WRF-hydro should put a priority on software design and engineering with a commitment to creating a sustainable software infrastructure that is well maintained, documented and also includes input from the community.
    - Establish clear guidelines as to how contributions are evaluated and what rules they must adhere to. Examples would include, but are not limited to, code styling, documentation standards, and guidelines for code review.
- Scientific recommendations—OWP should guide community involvement to address the following to strengthen the NWM/WRF-hydro:
    - Sensitivity analysis should be the basis of decisions as to priorities for development of the NWM and WRF-hydro models.
    - Data assimilation for problems related to the NWM/WRF-hydro should be pursued.

Biography

Dr. Kyle Mandli is Assistant Professor of Applied Mathematics in the Department of Applied Physics and Applied Mathematics and affiliated with the Columbia Data Science Institute. Before Columbia he was at the University of Texas at Austin where he was a Research Associate at the Institute for Computational and Engineering Sciences working in the computational *hydraulics group. He received his Ph.D. in Applied Mathematics in 2011 from the University of Washington studying multi-layered flow as it applies to storm-surge simulation. His research interests involve the computational and analytical aspects of geophysical shallow mass flows such as storm-surge, tsunamis, and other coastal flooding. This also includes the development of advanced computational approaches, such as adaptive mesh refinement, leveraging novel computational technologies, such as accelerators, and the application of good software development practices as applied more generally to scientific and engineering software.*

2.3.5 David Tarboton

Professor
Utah State University
Civil and Environmental Engineering
Utah Water Research Laboratory
dtarb at usu.edu

Recommendations

Pursuing the adage that "you cannot manage what you do not measure," establish simple quantifiable metrics for the NWM that address the question "How good is it?" While there are a lot of dimensions to this question, it is important that these be aggregated (weighted) into one or a few simple measures that support overall tracking of improvements. Weights used in aggregation may reflect priorities and may be expected to be adjusted over time.

- Skill metrics, or components of skill metrics should align with the goal of impact decision support services (IDSS) by being based on quantities of impact in decision making.
- Metrics should encompass external (third party) use of NWM outputs and use and effectiveness of the system at delivering outputs through web services to a spectrum of consumers (from academia to news media, e.g. Weather Channel).
- Metrics should encompass measures of engagement with the target communities (e.g. academic research, non-governmental, commercial, other agencies).
- Tools that evaluate metrics should be open and disseminated in an easy-to-use way so that they can be used to quantify sensitivity, and objectively evaluate improvement alternatives offered by the community.

Recognizing that there is uncertainty in almost all forecasts, ways to quantify and communicate uncertainty need to be prioritized. Some of these could include:

- Provide the statistical context for forecasts to allow forecasters to interpret model guidance and avoid blunders. As a possibility here, consider providing, with each forecast variable, the quantile of that value relative to retrospective model results, or historic data. Then forecasters, taking model results as guidance, and providing interpretations, can filter based on these quantiles and may be able to avoid blunders when, for example, an outlier is modeled, without any apparent reason, but still retains outliers, when for example, high quantile forecasts are coming out but there are accompanying high quantile forcing inputs. For example, if a high quantile flow is predicted, without high quantile rainfall upstream, this is a possible blunder or false positive, but if a high quantile (greater than ever seen) flow is forecast, and there is also high quantile rainfall upstream, then the forecast should be considered seriously.

- Develop capability for, and expand the use of ensembles. The parameters of hydrologic models, even physically based hydrologic models, are frequently unknown and unknowable. For example, even though we know the equations for flow of water through soils, we do not know the properties of the soil (conductivity, porosity, etc.) at the scale it is being modeled, and do not have an ability to measure these. Model calibration is a common approach to address this, searching over the space of possible valid parameter values, for those that are consistent with observations. However, it is common for multiple parameter sets to produce outputs close to observations, resulting in an identifiability or non-uniqueness problem (sometimes termed *equifinality*). This problem is compounded as greater spatial variability, and thus greater ability to incorporate spatial degrees of freedom into models, is developed. Uncertainty across equally likely parameter sets is commonly addressed through ensemble simulations with multiple realizations being produced to quantify this uncertainty. This can be computationally intensive and challenges the drive to model improvement through refining of the model resolution and explicit representation of increasing spatial detail. Hydrologic models are fundamentally different from atmospheric models in this respect, as the equations of atmospheric (fluid) processes and physical properties of the atmosphere are (believed to be) generally uniform. However physical hydrologic properties of watersheds and land surfaces vary spatially in fundamentally unmeasurable ways. This problem has received considerable attention in hydrologic research, with much NWS research, for example, on ensemble streamflow prediction. The computational challenges of applying ensemble approaches at the scale and spatial resolution of the NWM are formidable, but nevertheless should be considered, to be able to address and quantify uncertainty due to variability in indeterminate parameters.
- Following from the previous point and connecting to the need for impact-related skill metrics, there should be research to investigate and develop evidence to determine trade-offs between high detail in models with limited ensemble capability versus simpler models with greater ensemble and calibration capability in selecting the scale and configuration for the NWM.
- Recognizing that physical models do not quantify all the dimensions of hydrologic variability, there is an opportunity to leverage and couple with empirical, statistical, data-based machine learning approaches. Statistical learning approaches that strive to model differences between observations and model forecasts offer opportunities to improve forecasts by adjusting for bias (similar to statistical downscaling approaches in numerical climate and weather models) and to also quantify uncertainty.

The desire to engage with the community to expedite research to operations (R2O) has been stated. This represents a social challenge where the tensions between the desires for control, security, and management conflict with the openness that will encourage and nurture community participation. There is a famous email sent by Linus Torvalds at the beginning of the development of Linux asking for and inviting suggestions on this new free operating system being started (https://fossbytes.com/linus-torvaldss-famous-email-first-linux-announcement/). This is somewhat of a legend in the open source software sphere, and Linux is now a widely successful open source project that grew and benefited from community contribution. The point here is that in the setting up of mechanisms for community participation, a lot could be learned from the open source software movement. Open source is a set of software licenses used for openly available code. Open development goes beyond just code accessibility and is a development method for software that harnesses the power of distributed peer review and transparency of process. Open development is the community-led development model found within many successful free and open source software projects. Following are some recommendations of what I personally think could be done to strike the right balance:

- OWP and the federal government (NWC) have to be the gatekeepers of what goes into the operational NWM. But with this established, default to open. Apart from limited security sensitive information (such as dam operations) the code, configuration and data in operational versions, as well as past and candidate future versions, should be available for the community to examine, run (on their own computers) and evaluate.
- Review the literature on open source development and consider which aspects of that translate to NWM community development. Specifically, I suggest examining Raymond (2001, The Cathedral and the Bazaar) and Fogel (2005, Producing Open Source Software) to identify practices from the open source community that could transfer to NWM model community development.
- Use a version control system (e.g. Github) to openly manage the NWM code, to facilitate the transparency and access, and also to be precise about operational and candidate future versions. Include versioning information in all outputs to limit potential for confusion associated with cross version comparisons. Some of the approaches of David et al. (2016) may merit consideration.
- Motivating community participation is a key challenge in the social engineering of open source development and should be addressed. Here are some suggestions:
    - Establish procedures for community contributors to have the ability to meaningfully influence the direction of the project. This needs to be seen through the openness practices of the project. Contributions that have been demonstrated to result in improvements, through metric scores, need to be included, and seen to be included in the operational versions.
    - Decisions on improvements to be adopted, while by necessity retained in OWP, should be transparent and their basis documented (related to project goals and metrics) with consideration of community input.
    - Provide and support technical tools to lower the barriers to contribution. These could include easy-to-use subsetting tools, standard test cases, best of practice calibration and numerical solvers, common suite of tests and test metrics to compare results.

- Promote the rewards of participation, so that community members can see the value of participation and see "what is in it for me." Identify ways to enhance the impact of research that advances hydrologic modeling and prediction using the NWM framework by promoting the broader impact it can generate of value in writing proposals (e.g. through adoption), and increased citations (of value in academic promotion).
- Encourage, leverage and promote (support) activities of partners such as NCAR, CUAHSI, ESRI, and NCEI to repackage and redistribute NWM outputs, in standard and easily accessible formats and provide infrastructure to support and overcome some of the barriers in applying instances of the NWM configured for study watersheds. As one example, the CUAHSI-HydroShare project is already working on deploying WRF-Hydro configured as closely as possible to NWM in a Jupyter Notebook web app that can be run from HydroShare. We envisage researchers first selecting a study area (within US, e.g. CZO), extracting a subset of inputs to be able to run WRF-Hydro and reproduce closely NWM results for that area, and then for this to serve as a starting point for their research using the model. Note that the researcher's instance of the model would be running separately from the NWM, but research findings, framed in this context, should be in a format that could readily be adopted by the NWM if deemed of merit. This approach, by providing a platform with model, inputs, and dependencies already configured, and the potential to apply to large areas, eases entry to, and overcomes some of the difficulties researchers have in getting set up to start NWM-related research. It also provides an easy way for researchers to share and document their results for reproducibility and collaboration with others.
- Consider intercomparision exercises and community activities focused around specific problems or case studies as a way to promote and reward (through citations and reputation) participation in efforts to advance the NWM. There are many examples in the climate community. One example in the hydrology community is the Distributed Model Intercomparison Project (DMIP) (Smith et al., 2004).

The NWM is part of a broader set of services in water supported by the federal government. These services need to leverage capability from each other and this requires machine-readable automated exchange of information, i.e., a services-oriented architecture. The following is suggested:

- Work with partner agencies to embed the model in a common information infrastructure.
- Draw inputs from the services of other agencies where possible:
    - e.g., static inputs from terrain/hydrography served from USGS/EPA with periodic updates.
    - Dynamic inputs (forcing) as services that can be accessed by alternative models.
    - Develop a data service for the meteorological forcing engine outputs.

- Use data services (e.g. OGC) to provide access to outputs (e.g. WaterML, OpenDAP for NetCDF). With available software (i.e. THREDDS from Unidata), and outputs in NetCDF format this may be an easy-to-implement early activity.

There are also a number of technical suggestions to consider for improvement of the NWM.

- Evaluate options for deeper subsurface flow representations. The present representations of subsurface processes deeper than a few meters are limited, and this limits the ability of the model to represent the longer time scale processes associated with deeper storage of water.
- Improve the geographic and hydrographic data that serves to define the spatial geometry of the model. (This is sometimes referred to as hydrofabric). Current model elements defined from medium resolution NHDPlus streams and catchments are, in places, misaligned with higher resolution terrain, and the range of element sizes (catchments) is large, with some too small to be meaningful, and some too large to reasonably represent the hydraulics of flow in their corresponding reaches. Consider an underlying geospatial representation that is based first on a hydrologically conditioned digital elevation model (DEM) that has had blended into its best information from high resolution stream linework (NHD High resolution), and LIDAR terrain data when available, then derive the entire hydrofabric from this DEM (automatically), so as to be able to control element sizes and reach lengths. Coordinate with the USGS 3D elevation program in this work.
- Consider improvements to the representation of river geometry and ways to organize this information that enable updating as better information is collected. A standard data model, such as the OGC Common Hydrologic Features Model may be helpful here.
- Calibration, non-uniqueness of parameters, and ensembles were mentioned above in the context of uncertainty. There is also a need for research to relate model parameters to regional information, such as soils, geology and terrain, to assist with extending parameters to areas where there is no data for calibration, a process sometimes referred to as regionalization. Prior work on this topic with earlier NWS river forecast models may provide information and expertise for application to the NWM.
- Advance assimilation. Present NWM assimilation (if I understood it correctly) is limited to streamflow state variables. Measurements of streamflow do provide information on other model states, such as snowpack, soil moisture, and groundwater storage states. There is considerable hydrologic research on assimilation in the literature, and while there are challenges associated with quantifying relative uncertainty, more comprehensive approaches to assimilation need to be evaluated.

Other committee members have also written of the need for top 10 “challenges” with the model to encourage community investigation. In this regard, engagement with the international community, perhaps through the IAHS Unsolved Problems in Hydrology challenge https://iahs.info/IAHS-UPH.do, may be a vehicle for catalyzing research that may lead to advances in water prediction. These recommendations are long (and I am one of several committee members). Addressing all of these is too much for the current NWM team and underscores the need for community engagement to crowd-source the solution to water prediction.

References

- David, C. H., J. S. Famiglietti, Z.-L. Yang, F. Habets and D. R. Maidment, (2016), "A Decade of RAPID–Reflections on the Development of an Open Source Geoscience Code," Earth and Space Science, 3: 226–244, http://dx.doi.org/10.1002/2015EA000142.
- Fogel, K., (2005), Producing Open Source Software: How to Run a Successful Free Software Project, O'Reilly, 192 p, http://producingoss.com/.
- Raymond, E. S., (2001), The Cathedral and the Bazaar, Musings on Linux and Open Source by an Accidental Revolutionary, O'Reilly.
- Smith, M. B., D.-J. Seo, V. I. Koren, S. M. Reed, Z. Zhang, Q. Duan, F. Moreda and S. Cong, (2004), "The distributed model intercomparison project (DMIP): motivation and experiment design," Journal of Hydrology, 298(1-4): 4-26, http://dx.doi.org/10.1016/j.jhydrol.2004.03.040.

Biography

David Tarboton is a professor of Civil and Environmental Engineering, Utah Water Research Laboratory, Utah State University. His research focuses on advancing the capability for hydrologic prediction by developing models that take advantage of new information and process understanding enabled by new technology. He is principal investigator for the National Science Foundation project for the development of HydroShare, a collaborative environment for sharing hydrologic data and models operated by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). He has developed a number of models and software packages including the TauDEM hydrologic terrain analysis and channel network extraction package and Utah Energy Balance snowmelt model. He has been on the faculty at USU for 28 years where he teaches Hydrology and Geographic Information Systems in Water Resources.

2.3.6 David Maidment (CAC-WP Co-Chair)

Department Chair, Civil Engineering
University of Texas at Austin
maidment at utexas.edu

Recommendations

- Technical capabilities of the National Water Model:
  - Make a list of the Top 10 science challenges that you face in developing the National Water Model and develop a short description of each. Provide this to CUAHSI so that it can be publicized within the academic community.
  - Build a National Water Model component library so that components for individual processes such as overland flow, channel routing, etc., are separated from the main NWM code and can be operated and tested independently.
- Evolution of OWP water resources data services:
  - Provide a clearer definition of the public/private interface between what is developed and offered by NWS, and what is provided to the private sector and other users so that they can build their own NWM-based maps and services.

    - Prepare to ingest observation data services from a *network of networks* of observations data on streamflow and water level, not just from the USGS. This is critical to achieving streamflow forecast accuracy comparable to or better than that offered by the existing RFC models.

- Impact-based decision-support services using enhanced GIS information:
    - Focus on an ultimate strategic goal of an inundation depth map across the whole landscape, not just inundation associated with the river flooding and coastal storm surge.
    - Engage with partners in developing a 3D National River Morphology Dataset that accurately defines river channel bathymetry and the topography of the surrounding floodplain. This is analogous for inland waters to the topo/bathy mapping of the coastline that was achieved over the past few years.

Biography

David R. Maidment is the Hussein M. Alharthy Centennial Chair in Civil Engineering at the University of Texas at Austin, where he has been on the faculty since 1981. He participated in the first scientific meeting held at the National Water Center in May 2014. Following that meeting, he proposed what has become an annual Summer Institute for the National Water Center Innovators Program organized by CUAHSI, in which 105 graduate students from 49 universities have conducted research projects to enhance the National Water Model.

2.4 Private Sector

2.4.1 Matt Ables

Chief Executive Officer for the North American subsidiary
KISTERS
Matt.Ables at kisters.net

Recommendations

- The National Water Model provides a forecast point density 750 times greater than the existing production models, yet it still relies on the same network of USGS stream gauges for verification and calibration. Many third-party agencies, municipalities, river authorities, etc. operate and maintain additional stream gauges which could be included in the National Water Model. Inclusion of third-party stations provides a variety of business opportunities for the private sector and would allow consulting firms, monitoring equipment manufacturers, and software companies to offer services that would benefit both the client and the National Water Model. The USGS is recognized for providing unsurpassed quality and reliability of data, the standards of which many third-party groups will not be able to meet. Therefore, the recommendation is to generate multiple grades of data. Each grade would have a clear set of guidelines and standards before third-party data is certified and accepted into the National Water Model.

- Part of providing a set of guidelines and standards to the private sector includes the creation of a clear and public communications plan. With the many Federal agencies and researchers involved in the National Water Model, having one primary source/location of official communications is recommended. All parties involved in the National Water Model should be providing a clear and consistent message about the status, planned development, opportunities, and locations of additional information and resources. Third-party involvement will increase and can provide direct benefits to the National Water Model efforts if information about development standards, new value-added services, and release plans are clearly communicated.

- The creation of the National Water Model presents a compelling story of the Federal Government's response to join with the academic research community to develop new methodologies and enhance prediction capabilities in an era of increased extreme weather events and increasing population. Publicizing these efforts will bring a significant amount of support and involvement from all areas of the economy. Many entities, both public and private, will want to capitalize on these market efforts. Setting standards on how to reference the National Water Model in press, publications, and marketing materials is recommended. Without clear guidelines, the overall message and goals of the model could become clouded and damage public support.

Biography

Matt Ables is the Chief Executive Officer for the North American subsidiary of KISTERS. Founded in 1965, KISTERS has been developing hydrological, meteorological, and environmental data management software since 1985. Mr. Ables began his career in 2000 as a Hydrologist with the Lower Colorado River Authority in Austin, Texas, where he helped maintain stream gauges and served as systems administrator for the KISTERS hydrological database and software. In 2008 he joined KISTERS in Sacramento, California, as Project Manager and Consulting Hydrologist. He was responsible for designing and implementing hydrological data management systems across the U.S. and Canada. Now as CEO, he manages day-to-day operations and oversees larger projects including software deployment at several state and provincial agencies, hydropower operations, municipalities and water districts. Mr. Ables has 18 years of experience in hydrological data management, a Bachelor of Science in Geology from Baylor University, and a Master of Science in Geography from Texas State University. He is a registered Professional Geoscientist in the State of Texas.

2.4.2 Steve Kopp

Senior Product Engineer
Esri Inc.
skopp at esri.com

Recommendations

- Improve model accuracy with in situ data:
    - Include additional gauge networks in the model.
        - Thousands of additional gauges exist from Federal, state, and local agencies.
        - Standards exist for sharing gauge information as web services.

        - Drive initiative through existing Open Water Data Initiative or some other appropriate vehicle.
        - National Water Model team should define minimum guidelines for inclusion.
    - High return on investment for gauge owners to be included because it will improve flow forecasting in their area.
    - Organizing multi-source gauge data will benefit many other water resource initiatives.
- Study importance/sensitivity of channel parameters. How much information is needed to improve the model, and where is the diminishing return? It would be easy for the research community to spend significant time on methods for extracting detailed channel parameters from remotely sensed data, but it is unclear if doing so would significantly improve the skill of the model. Before significant time is spent on developing a national dataset of channel characteristics, it would be helpful to know which parameters are most important and how much impact they might have on improving the model.
- The explanation provided in the meeting of focusing National Water Model output on Impact Based Decision Support, delivered as web services, is in line with current and near future technology trends and strongly encouraged. This will provide value-added business opportunities and is also the public face of NOAA and the model. If this is attractive and easy to interpret and use, answering stakeholder's key questions, it will have significant impact and value.

Biography

Steve Kopp is a Senior Product Engineer at Esri Inc, an international geographic information system (GIS) software and services company. For more than 25 years Mr. Kopp has been part of the Software Products division at Esri, engaged in design, development, and management of GIS software. His primary focus is spatial analytic tools and spatial modeling applications, with a focus on Earth science applications, especially water resources. This work has led to long-term collaborations with Federal agencies, academia, and partner companies, toward developing specialized software for hydrologic analysis. He is currently co-chair of the Technology Committee for the American Water Resources Association.

2.4.3 Joseph Nimmich

Maritime Awareness Subject Matter Expert
Booz Allen Hamilton
Nimmich_j-asst at bah.com

Recommendations

National Water Service mission is to provide weather, water and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy. The Office of Water Prediction needs to focus on water forecasts and warnings.

- Recommendation 1: Focus the National Water Model on early projection of impact of events likely to cause major inundation for communities, to take mitigation actions to reduce impacts and prepare for response. This requires focusing the Modeling capability on earlier predictive capability. During-event modeling support can be provided to local/regional responders but as only one input to the local situational awareness effort. The National Water Model needs to serve a wide user group from first responders, to floodplain managers, city planners, to commercial services such as insurance providers, to an ever-expanding clientele.
- Recommendation 2: Users need to be able to access the National Water Model for local and commercial utilization including modifying with local data from sensors and local observations.

Biography

Joseph L. Nimmich joined Booz Allen Hamilton as a Senior Executive Advisor in April 2017. Prior to this, he served as Deputy Administrator of the Federal Emergency Management Agency (FEMA) from 2014 – 2017, where he focused on strengthening and institutionalizing the Agency's business architecture to achieve the FEMA mission, including actively modernizing information technology systems, instituting data analytics to enable evidence-based decision making, enhancing communication, and building a broader and more diverse workforce. Nimmich further played an instrumental role in establishing and facilitating several Agency governance structures to provide FEMA's program offices with a practical and collaborative approach to identify inefficiencies and gaps in decision making, the ability to make decisions strategically and transparently, and in a manner that benefited the organization as a whole. Between 2013-14 Nimmich was the Associate Administrator for the Office of Response and Recovery, responsible for directing the Response, Recovery, and Logistics Directorates, as well as the Office of Federal Disaster Coordination. He coordinated and synchronized all of FEMA Headquarters' operational response activities during major disasters and/or emergency activations.

He served in the U.S. Coast Guard for more than 33 years, retiring as a Rear Admiral in 2010. His assignments included the First Coast Guard District, based in Boston, Massachusetts, where he was responsible for all Coast Guard operations across eight states in the northeast and 2,000 miles of coastline from the U.S.-Canadian border to northern New Jersey. Nimmich earned an MBA from the Stern School of Business at New York University, and holds a master's degree in Strategic Studies from the U.S. Army War College. He received his B.S. History and Government from the U.S. Coast Guard Academy.