Report of the Community Advisory Committee for Water Prediction

2nd Meeting - Recommendations

November 20-21, 2019

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Community Advisory Committee for Water Prediction (CAC-WP)
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Introduction

The Community Advisory Committee for Water Prediction (CAC-WP) was formed in 2017 to provide the National Weather Service (NWS) Office of Water Prediction (OWP) with independent review of OWP's water modeling capabilities, with emphasis on the National Water Model (NWM), other modeling innovations and developments, and related data and information services. The CAC-WP was established and is managed by the University Corporation for Atmospheric Research (UCAR). The Committee is designed to bring independent expertise and perspectives from across the community to provide recommendations to improve OWP's modeling capacity and related services. The Committee maintains two co-chairs and approximately 12+ additional members composed primarily of hydrologists, civil engineers, and other water resources science and data experts. The Committee serves in an advisory capacity to OWP and NOAA and is not a formal federal review board. The foci for this second annual meeting included: current status of the OWP, NWC, and the National Water Model (NWM); active discussion by members and participants; recommendations and observations by Committee members, as well as involved experts in the National Water Modeling effort.

The mission of the OWP is to collaboratively research, develop, and deliver timely and consistent state-of-the-science national hydrologic analyses, forecast information, data, decision-support services and guidance to support and inform essential emergency management and water resources decisions. That mission is supported by the vision of a water-ready nation, capable of addressing a host of challenges with water extremes, water scarcity, and water quality via improved water prediction and decision support services. OWP is an office within the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce, and its mission is derived from NOAA's Water Initiative overarching goal to transform water resources prediction and information service delivery to better meet and support evolving societal needs.

The National Water Center has now been in operation for five years, having opened its doors in 2014. The NWC coordinates, facilitates, and integrates development activities across National Weather Service hydrologic services. It supervises 140 employees in three locations: Chanhassen Minnesota; Silver Spring, Maryland; and Tuscaloosa, Alabama. It provides critical key support for 13 River Forecast Centers (RFCs), and 142 weather forecast offices (FOs) across the country, as well as essential support for the Federal Emergency Management Agency (FEMA). In large scale and severe events, the NWC coordinates with field offices to ensure a common operating picture for all of the offices, assists with media inquiries to provide a national perspective, provides briefing materials, safety and awareness information, and prepares and delivers ad hoc data and related support services.

Since the January 2018 inaugural meeting of the CAC-WP, cross-agency coordination has resulted in recent agreement among the U.S. Army Corps of Engineers (USACE), United States Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), and NOAA's Office of Water Prediction (OWP) for development of one coordinating flood inundation mapping activity, to be mediated by the National Water Center. This spotlights the need for broader application of the NWM in operational settings, and reveals increased community interest for access to and participation in helping to further refine NWM parameters.

The OWP has a unique opportunity to further improve federal coordination and collaboration in the water sector to address 21st century water resource challenges and to provide informed decision support services (IDSS). Issues such as water security, analysis, and prediction of hydrologic extremes continually increase in magnitude, impacting all sectors of our society and myriad stakeholders throughout the nation.

Engaging stakeholders in co-creation of improvements in development of the National Water Model is critical to the overall goals of building a Weather Ready Nation: building resilience, readiness, and responsiveness across multiple sectors and enabling planning for adaptation, mitigation, and overall national security.

Meeting Structure

The meeting took place over two days at the National Water Center (NWC) in Tuscaloosa, Alabama: Wednesday, November 20 and Thursday, November 21, 2019. Thirteen Committee members attended in person and two members who could not attend provided written comments. Information was provided by the Office of Water Prediction and critical technical personnel from the NWC and from UCAR/NCAR. The meeting was co-chaired by David Maidment (University of Texas, Austin) and Don Cline (U.S. Geological Survey).

Day 1 provided review of the Committee charter and expectations; an extensive overview covering context, vision, and strategic goals of the NWS OWP (Tom Graziano, Director; Ed Clark, Deputy Director and Director NWC; Trey Flowers, NWC Analysis and Prediction Division). The overview included current status, capabilities, and accomplishments for the various versions of the National Water Model implemented to date. An extensive discussion followed centering on need and feasibility for the establishment of a *community developmental testbed* and *governance*, led by Don Cline; and discussion of improved representation of physical processes in the NWM led by David Tarboton (Utah State University), augmented by technical presentations and discussion on NWM capability by NWC's Trey Flowers, and NCAR's David Gochis.

Day 2 provided brief summaries of CAC-WP member feedback and observations on current status and opportunities for improvement; formation of three breakout groups with reporting on three primary topics, and extended discussion of primary recommendations emergent from the meeting.

Breakout group topics:

1. *In-situ and remotely sensed observations* for assimilation and model variation: current status and future plans (Harry Cikanek, lead: NOAA NESDIS SAR: Center for Satellite Applications and Research).
2. *Physiographic data sets* such as terrain data, stream network, land use land cover, soils data, and other relevant data sets (Richard Hooper, lead: Tufts University).
3. Demonstration of new *NWM post-processed data services and associated Flood Inundation Mapping capability* (Steve Kopp, lead: ESRI, Geographic information system mapping (GIS), software, and platform provision).

CAC-WP 2018 Report Recommendations

The commonalities and recommendations from the prior 2018 CAC-WP report centered on:

- Evolving the NWM to improve representation of physical processes and improve forecast accuracy for a range of hydrologic events from low to high flows; this would involve embracing regional test basins for model development and evaluation and support and pursuit of improved representation of channel bathymetry.
- Support establishment of an Agile Community Development Environment (ACDE) with common data structure and governance. Common data models facilitate community understanding; we should learn what we can from the open source community.
- Pursue and demonstrate a national Flood Inundation Mapping (FIM) capability.
- Bring capabilities to market (private and research sectors); don't be paralyzed by the pursuit of perfection.
- Expand and improve access to big data and educational opportunities.
- The private sector, like the research community, is a capable and willing partner.

Day 1 OWP Overview

OWP Director Tom Graziano provided OWP background, complemented by OWP Deputy Director/NWC Director Ed Clark's overview presentation on the National Water Model (NWM), including background; authorizations; key partnerships; a technical presentation on the model structure, its development and current capabilities; as well as desired future development; and relevant departmental and NOAA planning, including the NWS Strategic Plan 2019-2022 and its water-specific goals:

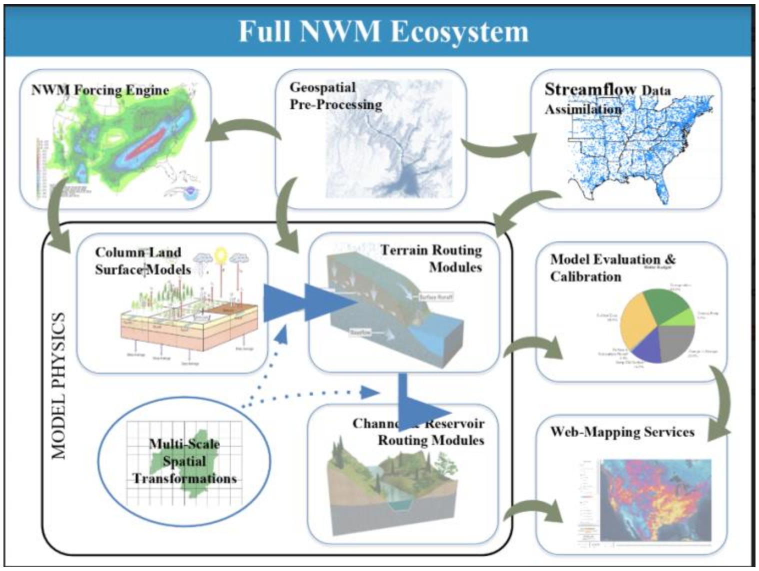
- Delivery of actionable water resources information from national to street-level and across all time scales;
- Provision of minutes-to-months river forecasts that quantify both atmospheric and hydrologic uncertainty;
- Improvement of forecasts of total water in coastal zones via linkage of terrestrial and coastal models with the National Ocean Service;
- Delivery of forecasts of flood inundation linked with other geospatial information to inform life-saving decisions.

National Water Model Ecosystem and Versioning

Trey Flowers of the NWC and Dave Gochis of NCAR/RAL shared further details of NWM operations, first implemented August 16, 2016, now three years old, providing operational forecasts to over 5 million river kilometers.

Gochis gave an overview of the full model ecosystem: forcing engine; geospatial pre-processing; streamflow data assimilation; and the NOAH-Multiparameterization land surface model (Noah MP) processing vertical atmospheric inputs; noting that channel and reservoir routing modules are an area ripe for improvement. Model physics include: column land surface models; terrain routing modules; multi-scale spatial transformations; and channel reservoir routing modules. Additional modules comprise model evaluation and calibration and web-mapping services. The model utilizes NHDPlus catchment aggregation [EPA Medium Resolution National Hydrography Dataset+ .]

There are programmatic needs for medium-resolution data; the EPA team is taking high-resolution attributes and working on infusing (pruning; generalizing) those into a new medium-resolution NHDPlus that will reflect some of those attributes; it would have some capability for future high-resolution improvement. Shelley Thawley with EPA suggested follow-up interaction between the NWM team and EPA to ensure that NHD3+ work is coordinated and parallel. David Maidment suggested further discussion about medium to high resolution (what about 3D representation in the internal model itself rather than post-processing?).



Flowers continued with a summary of NWM versioning from v1.0 in August 2016 (water resource model for 2.7 million stream reaches), to v1.1 (first upgrade) in May 2017 that increased cycling frequency and forecast length, initial calibration, and improved soil/snow physics. The v1.2 second upgrade was implemented in early 2018, providing extensive calibration, improved hydrofabric (terrain and stream connections), and improved data assimilation; the current version in operation is v2.0 implemented in May 2019 that includes expansion to Hawaii, medium-range (10 day) ensemble configuration, improved physics and calibration, longer analysis cycle, and enhanced code modularity. A fourth upgrade is projected for v2.1 to be operational in about one year (Fall 2020). It will expand to include the Great Lakes region, Puerto Rico, and the Virgin Islands.

Extended discussion followed on *flood inundation and ponded water* and levels of decision-making that might utilize ponded water indicators. There is potential for a post-process hybridized approach to address critical variables for multiple methods of water access: run-off production, infiltration, inundation. It was suggested that it would be equally important to improve infiltration parameters. NWC is on the cadence of producing an update on the model every year. Improving soil factors is included in Version 3 projections, along with subsurface processes; channel routing; compound water forecasting (fresh and salt); improved infiltration scheme; refactoring of NOAH-MP infiltration approach; distinctions between runoff and infiltration; improvement of the shallow ground water model, coupled with surface water model; improvement of current NWM bucket model. Maidment noted that, in line with a prior committee recommendation of forming sub-committees or study groups as needed, this is a potential mechanism to address the issue of *flood inundation and/or ponded water parameters*, to gain the best information possible.

Flowers included briefing on two future projects targeted for deployment in 2022: inland hydrologic and hydraulic routing, and coastal hydraulics and coupling (freshwater-estuary-ocean model coupling in the forecast model). These will enable greater capability for compound flooding involving freshwater, storm surge, and tides. Gochis provided additional input on future versioning, to include a fast-track for harmonization across different approaches regarding channel geometry. A parallel track is utilizing NOAA Joint Technology Transfer Initiative (JTTI) funding opportunities for incorporating data into forecast modeling and for model coupling to improve weather forecast operations; one focus would be on developing channel parameter metrics.

Discussion included *exploring all federal work* to develop a methodology to incorporate and/or extend broader work to incorporate channel geometry as well as bathymetry for calculating soil moisture and true land surface, atmospheric, and hydrologic integration. There was favorable comment on the progressive improvement of the National Water Model. The same kind of improvement applied to incorporation of the hydrofabric data and factors is a hoped-for progression. *If NWC can articulate its NWM schedule and advise the community of that, the community can gain a better understanding of how to jive with NWC priorities for next generation improvement*. One example of potential incorporation might be the University of Texas work on flood inundation mapping, where a national channel geometry dataset could be emergent from that work. Bringing in additional work and studies at other locations begins to create a broader picture for community participation in NWM integration. Clark noted that defining operational requirements would need to be part of those discussions. He also noted the experimental flood inundation mapping capability created by the NWC during the Texas flooding of September 2019 as an example of essential community engagement that needs more thought: how best to utilize regional center expertise and feed it back into the NWM.

Other stakeholder priorities include provision of consistent, high resolution ("street-level") analyses, predictions, and data to address critical unmet information and service gaps, and the transformation of such information into actionable intelligence by linking hydrologic, infrastructural, economic, demographic, environmental, and political data. Integrated understanding of near- and long-term outlooks and risks for flooding, drought, water availability, water quality, and climate change impacts are necessary.

Day 2 Reporting and Discussion: Community, Governance, Data

Advancing Water Prediction Science and Services

Don Cline introduced a session on efforts toward the *establishment of community engagement and governance* with the National Water Model, and the potential for the development of a community testbed. The USGS has commissioned the National Academy of Sciences (NAS) to report on future water needs for the nation and the most pressing water resource issues, which will grow more acute, and have greater impact with consequences for more people. These developments indicate that water resources prediction is raised to a national level of concern. The selection of WRF-Hydro as the core of NWM was made because it already had an existing community. It is now critical to integrate community development with the National Water Model. In the context of national water awareness and community modeling, the recommendations of this group are essential. With community engagement and participation, the deeper issue will be governance—*a federal capacity driven by an integrated community approach that is sustainable*.

Extensive discussion followed on the idea of a testbed approach for NWM development and community engagement. UCAR Community Programs (UCP) Director Bill Kuo provided background on the NOAA Developmental Testbed Center (DTC), for which he was Director from 2008-2016, potentially serving as a model for community engagement and process development The DTC transitioned research-to-operations (R2O) capability for numerical weather prediction (NWP). It was a support center for the community, providing software instruction and related support. Obstacles included: establishing a new paradigm for the transfer of code and associated processes via cloud computing vs. the prior paradigm of enabling downloadable code to various groups and individuals, which fosters the creation of different libraries, compilers, and out-of-sync systems development that is difficult to operate, update, and to consider down-stream effects. *To make research operationally relevant, the data to do so needs to be provided.* Forcings data has to be available, so that it is a realistic environment.

Data Discussion

Matt Ables of KISTERS reported to the group on *time series support for flood forecasting*. (KISTERS is a global software and technology solutions firm providing water resources, energy, and environmental monitoring and data management). All technology necessary exists to gather, validate (establish a quality control baseline), and publish 3rd party data for use in NWM. He discussed options that might be put in place around client data feeding into KISTERS overall data; it is backed up and stable—this was the procedure followed in a KISTERS collaboration with the European Centre for Medium-range Weather Forecasts (ECMWF). He commented further on the relationship of data to the validation process: if variances start to stray and deviate; some issue is at bottom; there are tools to check if the values make sense. One strategy is the way of big data: have enough data that the big anomalies drop out because they are noise.

- Clark noted that the issue OWP is facing is more about the validity of the data provided to WCOSS (Weather and Climate Operational Supercomputing System). In KISTERS vendorship to your agencies, are you providing a standard? Ables responded that that could be supplied as an option: e.g., client data fed into KISTERS overall data, backed up, and stable. This was the strategy with ECMWF. Clark noted that the stakeholders collecting this data are making economic decisions on KISTERS work; it has to be stable. That is a benefit to stakeholders: stable data availability.

Recommendations for community engagement and governance development

1. Gather recommendations about who and what constitutes *community* in this context, and who are the stakeholders.
2. *NWC identification of high priority items for development*; followed by issuance of calls for proposals addressing those needs, creating a competitive structure for community engagement. Be explicit about the challenges NWM/NWC face, and make known the need for some aspect, tool, or element of the model (e.g. groundwater), which can then become the focus of a call for funding.

3. *Support an instantiation of the NWM model for rapid access and open development*, so as not to endanger or impede the operational model, and plan for integration processes with the operational model as appropriate.

4. *The next barrier to community entry that can be overcome is to provide all of these engagement possibilities as a service*. When users are exposed to services—tools, pre-processing, post-processing—barriers start to dissolve.

5. *Communicate a common vision of needs, benefit, and timelines, for understanding, which involves long-range planning*, so that the operational world lays out needs, plans, etc. in order for the R&D community to contribute.

6. *NWM/NWC/OWP connections to other elements of NOAA development and/or interagency development* so that NWM community engagement is tied to the entire suite of tools, and provides attraction to the academic community.

7. *Seek some kind of agreement between agencies* that enables a common framework under which to operate.

8. *Continue and/or expand workshops for training, sharing elements, common frameworks, and advancing understanding.*

9. Ingest of more observation data may be needful. *What data sources are there that are not being utilized?* Potential sources include counties, storm water districts, hydroelectric companies; random monitoring groups; states, counties, local communities. With these varied potential contributors there will be variability in the data structures. Observational data provision from other sources could be a potential working group topic.

10. *Guidelines* should be developed to establish general rules on how to provide data to NWM.

11. *A public software roadmap and development plan* (5 years) is needed which lists products that will be developed with estimated timelines for NWM. This encourages 3rd party developers to plan for and build value-added products and services; assists the research community in planning resources and funding; and provides more transparency in communication.

12. *Develop a partnership and infrastructure vision of systematic governance for external community engagement* and how to provide such infrastructural support. Defining requirements; services; and participation opportunity need to be included. JCSDA [Joint Center for Satellite Data Assimilation] is a good example of multi-agency sponsorship and benefit. In kind contributions might come from academia: software engineering/software support; helpdesk and support desk; configuration management processes.

13. *EPA would appreciate being involved;* and has potential to contribute a water quality model; potential for funding contribution; and its experience with NHD3+.

Breakout Groups

The second day of the meeting enabled break-out groups to form, discuss, and report back to the whole group, followed by committee member reflections on the whole of the meeting. Breakout Group reporting summaries are available on the CAC-WP website, providing full detail of their discussions.

The three break-out groups convened on the following topics with indicated discussion leaders:

- Group 1 - Cikanek: In-situ and remotely sensed observations and data for assimilation and model validation; current status and future plans.
- Group 2 - Hooper: Physiographic data sets such as terrain data, stream network, land use cover, soils data, and other relevant data sets.
- Group 3 - Kopp: Demonstration of new NWM post-processed data services and associated Flood Inundation Mapping capability (Fernando Aristizabal, NWC).

Group 1 - In situ and remotely sensed data. Group discussion was led by Harry Cikanek, Trey Flowers, Matt Ables, Jerad Bales. The group first reviewed the current state of practice, including observations and data assimilation. Currently, only USGS streamflow observations are assimilated in the NWM. Discussion of gaps in observations and the potential to address those gaps was thorough and included both existing and potential additional sources for both in situ and remotely sensed observations. Recommendations for in situ data included *general needs for policy and practice development within a community-centered approach*; identification of potential need for unique approaches and *methods to be developed for acquisition of data from private entities; public authorities (states and local governments); other federal agencies*. For remotely sensed data, there is need to *identify types and forms of data required for assimilation, and a need to co-develop assimilation capabilities in a priority order*, with set up of operational delivery agreements according to R2O schedules. Additional identification of *types and forms of data required for validation and related products* and service level agreements are needed. Lastly, gaps in science were identified: specifically for model operation: *the NWM needs an assimilation system, and a validation system that is a diagnostic infrastructure and evaluation system*.

Group 2: Physiographic Data Sets: terrain data, stream network, land use land cover, soils data, and other relevant data sets – Rick Hooper. The group identified *objectives for flood forecasting and inundation mapping; drought forecasting; total water forecasting in coastal zones; and water quality, including point source/spills and non-point sources*. Each of these objectives could have potential outcomes across a range of attributes: NHDPlus/DEM; stream geometry; soils hydraulic properties; soil chemistry; aquifer hydraulics; aquifer geochemistry. Overarching challenges were identified for *surface data sets* (improved resolution vs. enhancements; incorporation of additional data; and for the more challenging area of *subsurface data sets* (online vs. offline use; reclassification of underlying data, and extrapolation of sparse observations.

Group 3 - Demonstration of new NWM post-processed data services and associated Flood Inundation Mapping capability – Steve Kopp. Group discussion included a presentation by NWC's Fernando Aristizabal on flood inundation mapping activity at the NWC (mission-central for real-time inundation mapping). The project intent is to provide interagency coordination and provide guidance to state/local entities on how to contribute and collaborate. The resulting data product will provide polygons of inundated areas with forecast time stamps; with intent for high value follow-on products. Such inundation mapping has high import for impacted populations; evacuation and rescue planning; roads and transportation methods to close affected areas; evacuation re-routing; number/type/cost of impacted structures; time until flooded. Ariztizabal and Kopp further summarized more detailed capabilities. Further discussion on multiple modeling approaches (RAS and related engineering approaches; HAND and similar approaches) followed. *It was recommended that guidance on appropriate use for the NWC effort be developed, and that NWC publish the data structure and share the rules for stream generalization*.

Examples of potential cross-collaboration include the Urban Flooding Open Knowledge Network (UF-OKN) NSF Convergence Accelerator project led by Lilit Yeghiazarian that is underway involving a number of universities mentioned by David Tarboton (https://nsf.gov/awardsearch/showAward?AWD_ID=1937099). The UF-OKN project is developing an information backbone that will integrate data (observational and simulated) across urban infrastructure, socioeconomic and public health sectors. It will make it possible to obtain actionable information for short-term and long-term flood planning using plain-English Internet queries. David Maidment provided a demonstration of the *UT-Austin inundation mapping capability utilizing Lidar data*; with possible uses to identify hydrofeatures such as flood plain encroachment. Researchers are using side-looking LIDAR to measure elevation of bridges and culverts.

Group 3 Actions:

1. Graziano requested a one-page description of the University of Texas - Austin OneMap project developed from HAND for predictive flood mapping and its application to NWM, and a statement of need (microdata, metadata) to enable further discussion about potential utilization.
2. Maidment and Thawley (EPA) will follow-up with further conversation about the UT project.
3. It would be helpful for some additional interaction or connection between FEMA data structure and the NWM; this should be mediated across the federal team.

CAC-WP Committee Contributions and Biographies

Following recommendations and observations are those of members and invitees in attendance at the November 20-21, 2019 meeting.

Matt Ables – KISTERS

Recommendations and observations:

As contributed in discussions with the group on Day 2, Ables recommendations center on data contribution and validation. All technology necessary exists to gather, validate (establish a quality control baseline), and publish 3rd party data for use in NWM. He discussed options that might be put in place around client data feeding into KISTERS overall data, backed up, stable, and therefore available. This procedure was followed in a collaboration with the European Centre for Medium-range Weather Forecasts (ECMWF). He commented further on the relationship of data to the validation process: tools and options for identifying sources of deviation and variance. One strategy is the way of big data: have enough data that the big anomalies drop out because they are noise. *Guidelines should be developed to establish general rules on how to provide data to the NWM*.

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 (Matt.ables at kisters.net).*

Jerad Bales – Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI)

Jerad Bales noted that the WRF-Hydro /NWM community is growing; both the NCAR team and CUAHSI have done much to build the community through access to code, training materials, and training courses. The community would benefit from a *stable set of input and output file formats* to encourage community development of pre- and post-processing routines that would be stable and shared widely. *Articulation of key science needs is also critical* in order for the community to know where best to engage. Performance testing in a broad set of settings and hydrologic conditions ought to be pursued with results published in the scientific literature. Regarding community governance, Bales voiced a caution to *not let governance be a barrier to community entry, so that scientists could engage in testing and enhancements, regardless of governance*. If a development team wishes to contribute to the code base, *then* governance becomes relevant.

Biography: *Dr. Jerad Bales is Executive Director of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). CUAHSI is a non-profit research organization representing more than 130 U.S. universities and international water science-related organizations. CUAHSI develops infrastructure and services for the advancement of water science in the United States, supporting the broad multi-disciplinary science community. Prior to his position with CUAHSI, Dr. Bales was the U.S. Geological Survey's Chief Scientist for Water. In this position, he was the Senior Executive responsible for $100M of activities related to the planning and development of national hydrologic research and technology transfer. He received his Ph.D. in Civil Engineering/Water Resources from the University of Texas (jdbales at cuahsi.org).*

Ana Barros – Duke University

Recommendations and observations:

While unable to attend the meeting in person, Barros provided the following observations to the group.

- Barros received very positive feedback from several of her students who attended a *NWM training course at NCAR*, and expressed appreciation of NCAR's efforts in modeling training.
- She suggested a *plug and play framework to exchange/replace model components* to test new parameterizations and submodels developed at universities. Changing model configurations provides another opportunity to better match NWM uses with performance skill as different physics and numerics may work well together for different types of applications at different spatial and temporal scales.
- *Testing and evaluation*: because the NWM is to serve operational needs and water services broadly, it is imperative that it be tested and evaluated thoroughly so meaningful metrics for different uses can be made available to users.
- *Working groups*: she encouraged action in the formation of working groups to address needs: "the model does not have to be perfect to be useful." Skill levels are likely very different for different applications across the full spectrum of water services envisioned by NOAA.
- Provide the committee and the community with *a synthesis report on current evaluation efforts, weaknesses, and strengths in performance and applications, and critical areas for research and targeted efforts including priorities set by the NWM team.*
- Barros expressed that there is an urgent need to create *open competitive research* funding opportunities to facilitate these activities and to bring in the intellectual critical mass needed to establish confidence in NWM robustness across regions and sectors and to develop a national community of independent users and stakeholders.

***Biography**: Dr. Ana P. Barros is the Edmund T. Pratt Jr. School Distinguished Professor of Civil and Environmental 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. She is President–elect of AGU's Hydrology Section and Chair of the Atmospheric and Hydrospheric Sciences Section of AAAS. Dr. Barros is a Fellow of the AAAS, AGU, AMS and ASCE, and a member of the NAE (barros at duke.edu).*

Pat Burke – NOAA National Ocean Service (NOS)

Recommendations and observations:

Current efforts across NOAA are focused on enhancing capabilities for compound flooding involving the coupling of freshwater, storm surge, precipitation and tides in support of the NOAA Water Initiative's (NWI) flooding and coastal inundation objective. However, the National Water Center and its partners still need to address questions about predicting what is in the water (i.e., water quality). While water quality is a component of the NWI vision, a roadmap needs to be developed to build this capability, and then be communicated to the broader water community to foster collaboration. The Coastal Coupling Community of Practice (CCCoP) has been created to serve as a nexus to mobilize this community to aid in strategic communication of the NWI vision and share information about scientific or technical advancements and best practices. It is comprised of practitioners across the Federal government, academia, and private industry.

There are many testbeds across NOAA supporting components of the NWS Unified Forecast System. NWC should either consider leveraging current funded testbeds and research programs, or develop an NWM community developmental testbed to engage other federal agencies, academia and the private sector with water interests. Funding would be administered to advance research priorities and transition capabilities identified by the NWI and appropriate cross-agency counterparts. This will also allow for better integration with the Earth Prediction Innovation Center (EPIC) and foster collaborative efforts to support multiple coastal coupling approaches to forecast storm surge, inundation and water quality. The NWM must remain agnostic to the type of model it is being coupled with, so the operational model coupling framework must remain flexible.

The NWC should develop an iterative modeling and observation approach as data assimilation methodologies improve. A gaps analysis should be conducted where the model should identify areas that could benefit from additional observations. The NWM will also help identify the core observations for operational implementation, which will lead to the development of standards for sustained observations; establish metadata and quality control criteria for these observations; and define evaluation metrics for model performance. These observations should also be available for experimental validation and testing by the community.

Biography: *Patrick Burke currently serves as the Chief for the Oceanographic Division for the NOS Center for Operational Oceanographic Products and Services (CO-OPS). CO-OPS is the authoritative source for accurate, reliable, and timely water levels, currents, and other oceanographic and meteorological information along the U.S. coasts and Great Lakes needed to support safe and efficient maritime commerce. CO-OPS also supports the NOS operational coastal ocean modeling program, which is working closely with the National Water Center to investigate freshwater-estuary-ocean modeling coupling approaches (pat.burke at noaa.gov).*

Harry Cikanek – NOAA NESDIS Center for Satellite Applications & Research (STAR)

Recommendations and observations:

NWS/OWP Context, Vision, Goals

- OWP and NWC described an extensive and apparently effective process to understand and keep track of stakeholder priorities, and *should continue to do so as a matter of routine practice*. Remarkable progress has been made in pursuing stakeholder priorities and advancing the National Water Model.
- Key partnerships are well recognized by OWP and NWC across the Federal and academic community, as well as internationally. Given the wealth of potentially useful data, and the ability to contribute to the overall mission, *OWP and NWC should consider expanded and more formal partnerships with the private sector, NGOs, state and local sectors; and consider forms of interaction that include CRADAS, cooperatives (like IOOS), commercial services, and interagency agreements.* Industries with a stake which from which OWP and NWC might benefit from a more formal relationship include insurance, hydropower, and transportation.
- OWP and NWC recognize the demonstrated payoff in adopting modern agile software development and community modeling, and should pursue proven mechanisms to implement them. *To help do so, OWP and NWC should align with NOAA and partner agency initiatives to continue progress toward making a community model approach to NWM a fully realized reality.*
- Major technical challenges in the NWM appear to be understood, and near-term systematic plans are in place to continue substantial skill improvement. However, *moving toward longer range planning out to possibly 10 years could provide great benefit in focusing the whole community on a common well-considered and well-understood roadmap. This should be based on effective well-analyzed collaboration between the R&D community and operational community.* Doing this could provide a disciplined approach to deliver advances efficiently and effectively. The example offered is ECMWF with their Global Forecast System R&D that works and aligns efforts from 10 year plans, helping make them the global model forecast leader.
- OWP and NWC displayed an appropriate vision for their role in Earth system prediction, and appear to have a realistic understanding of the challenges and key issues to address to continue to advance toward coupling between fresh and salt/atmosphere/land/hydrology. They also recognize the need to have diagnostics and metrics and have demonstrated effective R2O. *A key benefit of a community approach that could be harvested with what may be modest effort would be to have a formal component of the community modeling approach be workshops and outreach to the R&D community to describe operational challenges and payoffs as they are overcome, and to communicate and get feedback on longer range plans that the community can help shape, and can use to align resources so that they address R&D topics with operational impact.* The approach suggested is to take the ideas behind EPIC and the vision it represents for community modeling and work to implement it in the water community. There are several organizational/governance models which have made progress in this regard, including the MOM6, HWRF, JCSDA (management structure and models – JEDI assimilation system and CRTM radiative transfer model). It is extremely helpful for a developer to line up their efforts to meet a specific schedule for a known and well-planned transition to operations

opportunity, and for a researcher to work on a major operational challenge/barrier issue validated by operators to demonstrate linkage to outcomes with payoff to society.

- The NOAA Water Team and water initiative have made good progress in *establishing collaborations and partnerships*. Emphasis in continuing to grow and expand these, to make them formal and effective, could be very beneficial. An example that could serve as at least a partial model for how this might be done is the Joint Center for Satellite Data Assimilation (JCSDA), which under a formal MOA involves NOAA, NASA, Navy and USAF. They each contribute both funding and personnel to deliver various projects associated with satellite data assimilation for operational model system components of those organizations to select and transition to operations. Another model is the IOOS cooperatives which works across NOAA, other Agencies, and state and local authorities to predict and monitor coastal regions and provide services to a variety of users.

Community Development Testbed and Governance

- While a *testbed* is a critical component of community modeling, in order for community modeling to be most effective, the scope of what a testbed is needs to be appropriately expansive so as to *encompass a full "Center of ….." approach which provides standards, support, workshops, training, test bed, roadmaps, user engagement, communications, and outreach to fully and comprehensively engage the community so as to attract partners who provide value as well as receive benefit.* The vision and outline of EPIC represents this comprehensive approach, and should be pursued.
- Governance—the nitty gritty of management of community code development and its transition to operations—is recognized as a key challenge. *NWC should connect with efforts in NOAA addressing these issues*.
- It was recognized in the discussions with CAC-WP members that *there are other agencies that depend on progress in the NWM, that could contribute materially to the community and partnership. It is important to take steps to integrate them into full partnership.* Although the outreach and efforts of the OWP to create effective partnerships is to be commended, it is clear there is more to do and to be gained.

Improved Representation of physical processes in the NWM

- Machine learning was mentioned in several of the efforts and plans associated with physical processes, however, *a more concerted effort to pursue adaptation of the many mature approaches for AI/ML to water model challenges may pay big dividends*. The NOAA AI workshop showed several examples with payoff in atmospheric models and satellite remote sensing retrievals. *The next NOAA AI workshop is coming up in April, and participation is recommended to make connections which will aid progress in applying AI/ML.*
- Major improvements in satellite remote sensing capabilities, both on orbit and coming in the near future, coupled with many potential sources of untapped but valuable in-situ data could lead to better ways to represent physical process that are complex and difficult to address by current and conventional means. *Continuing the collaboration with NESDIS and others is recommended to enable effective utilization of new observational capabilities*

Biography: *Harry Cikanek is the Director for the United States National Oceanic and Atmospheric Administration's Center for Satellite Applications and Research (STAR). STAR is the unit of the NOAA Satellite and Information Service responsible for calibrating sensors and transforming raw and intermediate satellite data flows from NOAA and global observing system satellites into low latency weather and ocean environmental satellite-based data and information products. These feed forecast models, operations, personnel, and downstream value-added applications, and research needs in NOAA, its partners, and external users, and are essential to NOAA's mission to protect life, property, and livelihoods. Harry began this assignment in January 2017 to ensure successful transition to operations for GOES 16, GOES 17, and JPSS-1 satellite data products, and to chart a path to enable STAR to best harness the growing global observing system, emerging data product technologies, and the advent of commercial weather data for NOAA.*

Prior to his current position, Cikanek served just over five years as the first Director of the NOAA Joint Polar Satellite System (JPSS), stabilizing and streamlining the program to tighten its focus on the weather mission while avoiding over $2 billion in cost. He oversaw the successful transition of the Suomi National Polar Partnership (the first JPSS mission) satellite to NOAA operations and spearheaded adding Polar Follow On - JPSS-3 and JPSS-4 missions to the program. He began his career as a NASA aerospace engineer. NASA assignments included engineering and program management in rocket propulsion, launch services, space transportation technology, and human exploration of space. He holds two degrees in mechanical engineering from the Georgia Institute of Technology. He is the author or coauthor of over 25 papers and articles. He is also a recipient of the Presidential Rank of Meritorious Executive, the NASA Outstanding Leadership Medal, and is an Associate Fellow of the American Institute of Aeronautics and Astronautics (harry dot cikanek at noaa dot gov).

Don Cline – United States Geological Survey (USGS); Co-Chair, CAC-WP

Recommendations and observations:

The challenges faced in water science, and their impacts, are great. Cline believes we are approaching the end of Phase 1 of the NWM and the NWC. He frankly noted that the NWM is a small effort in an agency where water is not the highest priority. If we don't figure out how to achieve the community engagement we've talked about, we must do everything we can to continue the effort, or we won't get to the peak implementation we are all envisioning. *As a hydrologic community we must step up to the challenge for continuation and engagement.*

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.*

Cline 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. He has been in the Senior Executive Service since 2010.

Cline 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. Cline holds a Ph.D., M.S. and B.S. from the Department of Geography at the University of Colorado, Boulder (dcline at usgs.gov).

Clint Dawson – University of Texas, Austin

Recommendations and observations:

With a computational science and coastal modeling background, Dawson's interest is in coupling with the NWM in those arenas. He has worked on the Galveston area USACE project, which he elaborated on in the meeting: a mesh system for the upper Texas coast for coastal modeling and coupling between storm surge models and rainfall runoff modeled by HEC-RAS. His recommendations center on coupling the NWM (and other hydrologic models) to coastal models to predict compound flooding events where storm surge combines with rainfall-runoff. He is involved in a number of projects funded by different agencies (NOAA, NSF and USACE) addressing this issue. The NOAA project specifically is to address the coupling of the NWM with the ADCIRC coastal modeling system. In this regard there are many questions to be addressed including: how and where (in the physical domain) to exchange information between the models; which model will handle overland flow physics during inundation; how to incorporate other features such as stormwater drainage, infiltration, ponding, etc. There are also many software issues such as what coupling platform to use, how to run the codes simultaneously but independently, and more. *As the NWM model evolves, close collaboration between the developers and coastal modeling community is needed.*

Biography: *Clint Dawson is the John J. McKetta Centennial Energy Chair in Engineering, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, and head of the Computational Hydraulics Group in the Oden Institute for Computational Engineering and Sciences. 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 (clint at oden dot utexas dot edu).*

Efi Foufoula-Georgiou – University of California, Irvine

While unable to attend the meeting in person, Foufoula-Georgiou provided the following observations to the group.

Recommendations and observations:

- *Engaging the research community much more in all aspects of the NWM development, testing, and validation is necessary for this effort to gain momentum and growth*.
- Reflecting back to her participation in a RAL advisory committee at NCAR when WRF-Hydro was proposed and approved to move forward, her aspiration was that a WRF-Hydro model would do the same for the hydrological sciences community as WRF did for the atmospheric sciences community. Her impression is that we have not yet reached this point of community participation, in terms of using WRF-Hydro to generate ideas, papers, and advance research.
- If the use of the model is opened up to community participation, knowledge gaps and new ideas are certain to instigate more resources for basic research in hydrologic sciences.
- Participating in the recent initiative promoting an interagency effort to develop an Integrated Hydroterrestrial Modeling (IHTM) framework, she noted that this new effort should be openly discussed in conjunction with NWM, clarifying to the research community the status and goals of each and their synergies and collective value.
- *She noted that our community still fails for various reasons to make the point of the need for an open-source Community Hydrologic Modeling system (WRF-Hydro or NWM or IHTM) and get the buy-in of the academic community, funders and federal agencies. We need to change this; what will it take?*

***Efi Foufoula-Georgiou** is a Distinguished Professor in the Departments of Civil and Environmental Engineering and Earth System Science, and the Samueli Endowed Chair in Engineering at the University of California, Irvine. Her area of research is hydrology and geomorphology, with special interest on scaling theories, multi-scale dynamics of precipitation and landforms, and the interaction of climate and the terrestrial environment. She has served on several advisory boards including the Water Science and Technology Board of the National Academies; NSF Advisory Council for Geosciences; NASA Earth Sciences Subcommittee; Board of Trustees of UCAR; chair of the Board of Directors of CUAHSI; and President of the Hydrology section of AGU. She is a fellow of AGU, AMS, AAAS, and an elected member of the European Academy of Sciences and the U.S. National Academy of Engineering (NAE). Prof. Foufoula-Georgiou received a diploma in Civil Engineering from the National Technical University of Athens, Greece (1979), and an M.S. and Ph.D. (1985) in Environmental Engineering from the University of Florida, Gainesville (efi at uci dot edu).*

Rick Hooper – Tufts University

Recommendations and observations:

The NWM has demonstrated that continental-scale hydrologic modeling at high resolution is feasible for operational uses. However, improving forecasting skill is dependent on improved process modeling and better model parameterization To that end, engaging the academic community to use NWM, and specifically the NHDPlus hydrofabric as a research framework should be encouraged, and the NWS would benefit from this engagement.

NHDPlus has the opportunity to transform the way hydrologists view their science—from a series of studies of individual places to a more comprehensive and unified view of the hydrologic cycle with the continent acting as a "resistor" between the atmosphere and the ocean. Broadly, the academic community should be encouraged to move beyond continental-scale modeling simply as scenario analysis (as is done for climate prediction) or heroic scale computing, to using continental scale modeling in a hypothesis-testing mode with NHDPlus as the standard hydrofabric to improve comparability of results. Coupled physical models like PARFLOW and SUMMA lay the mathematical foundation for improved process representation (mostly for groundwater). Note that SUMMA is developing parameters sets based on NHDPlus. Although these models are not currently appropriate for operational use, the goal of using NWM for drought and especially water quality forecasting will require more realistic groundwater models.

The Office of Hydrologic Prediction could support convening conferences, such as Chapman Conferences, that would explore the frontiers of continental-scale modeling, together with other agencies such as the NSF and DOE. Future summer institutes could focus on NWM performance, particularly where there are dense gaging networks (such as in Iowa) to better understand limitations of the hydrologic and hydraulic process representations in the NWM. The results of these studies could spawn additional research. Hooper spoke about engaging the academic community via the NHDPlus: this was a transformational moment for hydrology; NHDPlus is a game changer. *Hypothesis testing: release to the academic community for evaluation: here are grand challenge problems. Market through convening a Chapman Conference or other venue for community engagement*. Data challenges: can we use the hydrofabric? how does groundwater work at continental scale? help organize existing information, and test.

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 served as Chair of the 2019 Gordon Research Conference on Catchment Science and Chair of the External Advisory Board for the Helmholtz Center's Terrestrial Environmental Observatory Network (richard dot hooper at tufts dot edu).*

Steve Kopp – ESRI

Recommendations and observations:

Kopp recommended *leveraging of interagency collaborations* to drive a community engagement initiative and to make it easy to access gage information from any authoritative agency: accessible as a web service, a single access point and API. This could be a federated (virtual) or harvested aggregation. Some basic agreement on required and recommended fields, etc. would provide a framework for state/local/commercial gage operators to be included; it simplifies access for the NWM team and everyone else.

He suggested that a CUAHSI/NWC Summer Institute would be a good venue for *advancing understanding around uncertainty of inundation maps*: an academic research project to understand error propagation from forecast models to inundation maps. This could inform project design decisions on spatial resolution and vertical accuracy. Additional related suggestions include how to visually convey data/model uncertainty to map users, and research to correlate historic modeled flow and inundation against field-measured or remotely-sensed historic inundations.

He suggested that from an industry perspective, a clear vision of future public data products is crucial. There seems to be a gap between what the NWC would like to provide as public data products and web services, and what they would like to do. Industry is hesitant to commit to a large effort to build and curate value-added products if there is a chance NOAA may deliver something similar for free.

Biography: *Steve Kopp is a Senior Product Engineer and Science Liaison at Esri Inc, an international geographic information system (GIS) software and services company. For more than 30 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 (skopp at esri dot com).*

Michael Lowry – Federal Emergency Management Agency (FEMA)

Recommendations and observations:

There is an overdue need by decision-makers for *national flood inundation guidance*. Prioritizing stakeholder needs (scale, timeline, etc.) is necessary. Is there any room for sacrificing fidelity for scale? (i.e. 70% solution is better than none).

Biography: *Michael Lowry serves as a Strategic Planner and Emergency Management Specialist for FEMA Region IV of the Federal Emergency Management Agency (FEMA). He is responsible for long-term strategic direction and response planning. Lowry has 15 years of experience in research, forecasting, communications, and emergency management. Prior to joining FEMA, he served as a subject matter expert on hurricanes and tropical meteorology, most recently as visiting scientist with the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC), through its partnership with the University Corporation for Atmospheric Research (UCAR). Previously, Lowry served as on-air hurricane specialist and tropical program lead for The Weather Channel (TWC) from 2012-2016. While at TWC, he provided network coverage for hurricanes and nor'easters, including Superstorm Sandy in 2012, the Boston blizzard in 2013, and Hurricane Matthew in 2016, filing reports for NBC Nightly News, TODAY, MSNBC, and CNBC. Lowry has also served as a lead scientist at the NHC in Miami, Fla., where he was responsible for the development of new tropical cyclone-related products, including new watches and warnings, for the National Weather Service (NWS). Other positions have included Senior Scientist at the Defense Threat Reduction Agency (DTRA) in Alexandria, Va., and emergency manager and meteorologist for the Florida Division of Emergency Management, where he provided support for nine presidentially declared disasters, including seven hurricane disaster declarations in 2004 and 2005. Lowry is the recipient of the 2013 National Hurricane Conference Outstanding Achievement Award in Meteorology. He holds a Bachelor of Science and a Master of Science in meteorology from Florida State University (michael dot lowry at fema dot dhs dot gov).*

David Maidment – University of Texas, Austin; Co-Chair, CAC-WP

Recommendations and observations:

WRF-Hydro and the National Water Model

WRF-Hydro is an outgrowth for applications to hydrology of a very mature framework called the Weather Research and Forecasting (WRF) model developed at NCAR that is widely used and well documented. WRF-Hydro itself has an impressive web site which contains applications world-wide, model code, technical description and user guides, terms of use, preprocessing code, test cases, meteorological and terrain data, usage tools, news items, online talks and webinars, training and materials, publications, events and announcements, community spotlight, and a user forum. WRF-Hydro is a framework for hydro-meteorological modeling that is used across the world (https://ral.ucar.edu/projects/wrf_hydro/overview).

The National Water Model is built using one particular configuration of WRF-Hydro for application in the United States. It has a very deep real-time computer operation behind it at the Weather and Climate Operational Supercomputer System (WCOSS) that is linked to the national weather forecasting system and continually updated with four model variants for current and anticipated future water flow conditions in 2.7 million stream reaches of the continental United States. As new versions of the National Water Model are produced, it becomes increasingly established as a foundation for national scale water forecasting in the United States. The National Water Model is described in a two-page document presented at https://water.noaa.gov/about/nwm and related links provide background about the Office of Water Prediction and a visualization tool for mapping the current National Water Model results.

It is obvious when comparing these two web sites that the background documentation of the WRF-Hydro framework far exceeds that of the National Water Model. Indeed, it could be said that if judged by the volume of documentation WRF-Hydro is a much larger and more mature computer system, shown in orange on the left of Figure 1, compared to the current version of the National Water Model shown in blue.

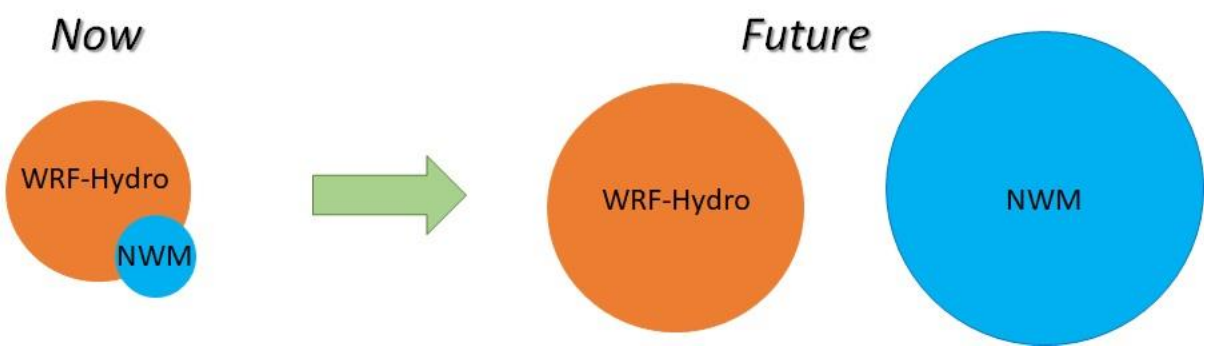


Figure 1. WRF-Hydro and the National Water Model

The National Water Model is currently (January 2020) about 5 years old—the prototype was developed using WRF-Hydro at the University of Texas at Austin in January 2014, and the first version being tested in the WCOSS was in January 2015.

If we think ahead 5 to 10 years, it should occur that a transition takes place so that the National Water Model becomes an entity independent of WRF-Hydro, and much larger in terms of documentation and accessibility, as shown in the right hand side of Figure 1.

Recommendation: *Develop a web site for the National Water Model that includes applications, model code, technical description and user guides, terms of use, preprocessing code, test cases, meteorological and terrain data, usage tools, news items, online talks and webinars, training and materials, publications, events and announcements, community spotlight, and a user forum*.

Management of the National Water Model Development

The development of the National Water Model is carried out by the Office of Water Prediction and by the WRF-Hydro group at NCAR. The framing of the development effort, decisions as to what to include and leave out, testing of model alternatives, etc., are carried out essentially exclusively by this team. Apart from the Summer Institutes, and the deliberations of this Community Advisory Committee for Water Prediction, there is little formally defined way in which the external hydrological community, including, in particular, other federal partners, can guide the decision making as to the model's development and application.

The separation of the two circles to the right in Figure 1, is meant to signal that in future years, the National Water Model should be managed independently of WRF-Hydro. In other words, if other federal stakeholders, such as IWRSS partners or EPA, wanted to invest in and guide some parts of the National Water Model development, there should be a governance process that is more open and inclusive than the current one that permits that engagement to occur. The National Science Foundation manages its large research entities by bidding them out for recompetition on a periodic basis. Indeed, the management of NCAR by UCAR is periodically rebid by NSF and UCAR has to win the right to continue to manage NCAR by winning this recompetition process.

Recommendation: The National Water Model development process should be more closely guided by a stakeholder group that includes key federal partners. The model development activity, presently based in the WRF-Hydro group at NCAR, should be opened to competition on a periodic basis so that other organizations or entities can contribute when appropriate.

Water Data Input to the National Water Model

A great deal of effort has been expended in each version of the NWM to improve the process science in the model but streamflow data input is still limited to USGS flows. Water level data in streams are not ingested—they are critical for flood inundation mapping, and are much more extensively measured than are flow data. Perhaps 80% of the water observations in the US are not currently being used. There is no doubt that predicting water conditions in 2.7 million stream reaches of the U.S. requires more continuously ingested water level and flow data than are presently being used. If organizations could see how their data was input to and reconciled with the National Water Model, they would be inspired to install more gages. The Texas Department of Transportation (TxDOT) has installed radar stream water level and velocity gages at 20 locations along Interstate Highway 10 to help enhance National Water Model forecasts of water conditions on this critical national highway, which has been closed for several days by flooding three times during the past four years. There are many local flood alert networks whose data are used by the regional River Forecast Centers but not by the National Water Center. There are at present no guidelines or computer system for quality control checking of data inputs beside that of the US Geological Survey.

Recommendation: *Establish rules and a mechanism for a data ingestion program that would allow regional and local agencies to contribute their water observations data to the National Water Model.*

Biography: *David R. Maidment is a Professor Emeritus of the University of Texas at Austin where he served on the civil engineering faculty from 1981 to 2019. In collaboration with the Consortium of Universities for Hydrologic Sciences, Inc, (CUAHSI) he led the engagement of the academic community in the initial development of the National Water Model, and was the technical director of the first three Summer Institutes held at the National Water Center. He received his Bachelor's degree in Agricultural Engineering from the University of Canterbury in Christchurch, New Zealand, and his M.S. and Ph.D. in Civil Engineering from the University of Illinois at Urbana-Champaign. In 2016 he was elected to the National Academy of Engineering for development of geographic information systems applied to hydrologic processes (maidment dot utexas dot edu).*

Joe Nimmich - Booz Allen Hamilton; formerly, FEMA

Recommendations and observations:

- The beneficiaries of the NWM are the National Weather Service, FEMA, and multiple other agencies, but ultimately, society as a whole: industry, agriculture, the general public. Broader community involvement is essential.
- Setting the stage for the future of the NWM depends on the demand signals received from those who have interest, investment, and engagement with helping to refine the capabilities of the NWM, beyond a strictly operational model.
- *The operational model has to meet the five-S test of a community model: stability; skill; speed; service; science, but the operational model should be separate from a developmental environment*.
- 80% of federal disaster money goes to water damages. Nearly 90% of deaths are water related. Drought damage is estimated to eventually be larger. The public at large is saying that these events are happening more frequently, not just emergency managers. The entire society/community is focusing on this problem and communicating it is essential. Some structures can be mapped out by which broader communities can be involved. *The ability for research and development to be involved in operations is critical*.

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) (2014-17) 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. in History and Government from the U.S. Coast Guard Academy (joe dot nimmich at potomacridgeconsulting dot com).

Roy Rasmussen – NCAR Hydromet Applications Program (HAP)

Recommendations and observations:

Rasmussen reported on very recent new research findings from NCAR related to a warm and dry bias in the central U.S. He showed that the bias was largely produced by lack of groundwater and the importance of resolving the water table (his experiments showed that a minimum horizontal grid spacing was required). Because of this research, NCAR has implemented a new groundwater scheme into NOAH-MP. Significant sub-grid variability is missed when using coarse resolution. *His recommendation is that by utilizing high resolution, one can also capture snowpack, snowfall, summer precipitation, and groundwater.* We have a 3km operational HRRR model running out to 18 hours. Why not recommend a longer forecast time, say out to five days? This would allow one to take advantage of the improved capture of the water and energy budgets that are relevant to running and improving the NWM. Along these lines, he recommends coupling of HRRR with the NWM to allow for feedback effects.

Biography: *Roy Rasmussen received a B.S. degree in Physics and Mathematics from Wheaton College, Illinois, in 1978, and a Masters and PhD from the University of California, Los Angeles, in Atmospheric Sciences in 1980 and 1982, respectively, specializing in cloud physics. After receiving his doctorate, he was an Advanced Study Program postdoctoral researcher at the National Center for Atmospheric Research (NCAR). He is currently a Senior Scientist and director of the Hydrometeorology Applications Program at the Research Applications Laboratory at NCAR. He is an American Meteorological Society Fellow and has ten patents and over 100 peer reviewed journal papers (rasmus at ucar dot edu).*

David Tarboton – Utah State University

Recommendations and observations:

There are three areas I would like to focus on where there are opportunities for improvement of the National Water Model: (1) Processes for Community Engagement; (2) Improving the underlying data; and (3) Improving the representation of model component processes.

Processes for Community Engagement

To engage the community, a structure and process for community contributions to be evaluated and adopted needs to be developed. Figure 1 adopted from git-flow processes illustrates one possible such structure.

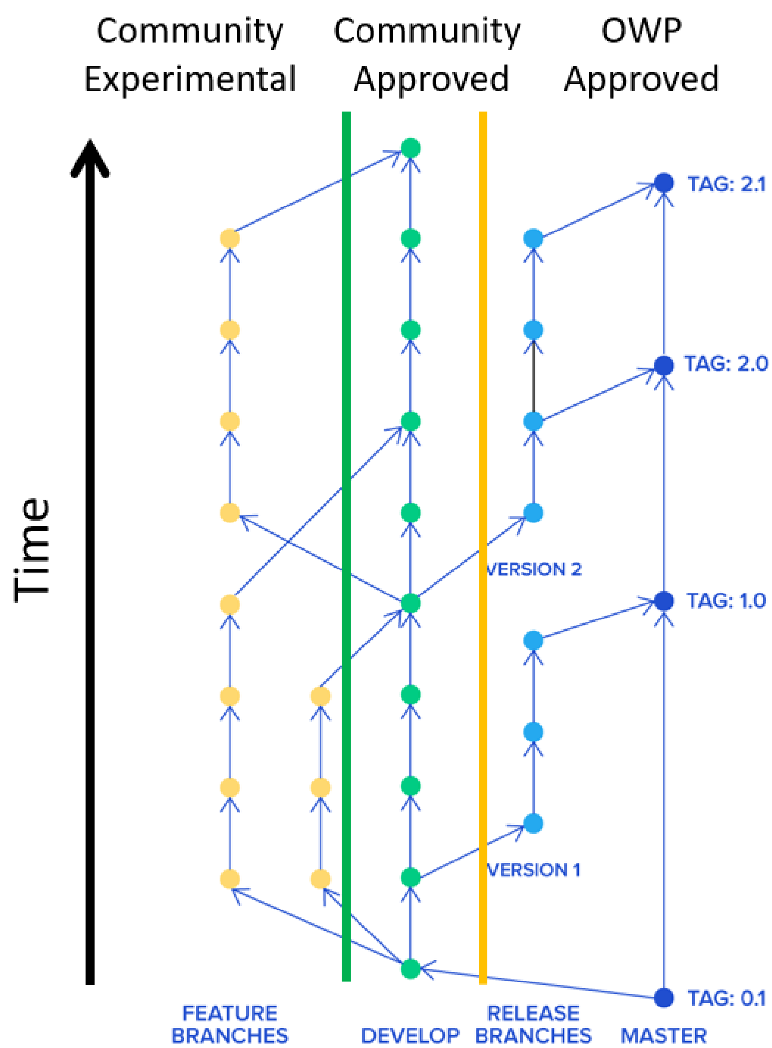


Figure 1. Suggested Git Flow Process for managing and merging of community code into official releases. Adapted from https://www.toptal.com/software/trunk-based-development-git-flow

In this figure time progresses from bottom to top and each dot represents a version of the model code or commit to git, if git is used for version management. On the right in blue, on the master branch are the official OWP approved releases each tagged with a version number. Code to the right of the vertical yellow line would be under the control of OWP and undergo strict review and testing. Apart from security elements, it would still be open for anyone to read. To the left of the vertical yellow line is the community process. A develop branch would be maintained that represents the integration of community contributions. A community or development approval team would oversee merging of experimental changes into the develop branch. To the left of the vertical green line are individual feature branches representing improvements that community members are testing. This works as follows. There is an initial master release (tagged as version 0.1). A copy of this is made to initiate the community develop branch. Community improvements result in improvements to this (second green dot from the bottom up. These are tested (by OWP) and result in three versions 1 trials (three light blue dots from bottom up). After successful testing these changes are merged into the master branch (version or tag 1.0). Meanwhile two community members start experimental or feature branches to develop improvements (perhaps different process representations). These are represented by the parallel sets of yellow dots progressing upwards to the left of the vertical green line. At some point these are tested and approved for merging into the Develop branch. Community governance needs to be established for merges to the develop branch. This might be through an organization such as CUAHSI. Merging into develop might occur after research papers documenting their contributions have been peer reviewed and published. Then after evaluation by OWP a candidate master branch for version 2 of the model is branched from the community develop branch, and undergoes further OWP refinements before being merged and released as the official version 2 (Tag 2.0).

The ultimate goal of such a process is an active community contributing to improvements in the NWM. The elements of this process that are important to its success include:

- Default to open. The whole process is transparent. There are many eyes on it that can identify problems.
- OWP maintains strict control of official releases. There is no requirement for experimental branches to be adopted, but there may be "pressure" where experimental branches have demonstrated their potential in peer reviewed publications.
- The process is welcoming of contributions. Researchers can see how their work may have an impact by being adopted. This becomes an incentive for research.
- Barriers to participation need to be identified and resolved. These could include knowledge of how one's contribution would be evaluated and if beneficial incorporated, documentation, and funding. A survey of potential community contributors may be helpful to identify other barriers.
- Community governance to approve the integration of contributions to the develop branch and evaluate and coordinate improvements suggested for the master branch. Community suggestions are non-binding as OWP has to have the final say over what goes in to the NWM, but community involvement would be encouraged if community researchers can see their work progressing into operations, or if there is transparency and well communicated reasons for innovations that are not adopted (e.g. if they are computationally too burdensome, or insufficiently general).

- Outreach to spread the message of how this process works and of opportunities for contribution and their impact. This could include workshops, conference presentations, papers and news articles, webinars and any number of scientific outreach activities.

There is sometimes a tendency for developing a community around a project to be deferred until the project is "ready", not wanting to have the project appear incomplete or premature. I think this is wrong. If a community process does not exist, the best time to start is now. If work is required to get things ready, make the tasks of getting things ready, community tasks.

Improving the underlying data

A model can only be as good as its input data. An important contribution of a model is the organization of data that it brings about. The input (or time variant forcing) data integrated from multiple sources to drive the NWM, are in their own right, valuable national datasets. Making these available to the community for use is helpful to the community and also promotes comparisons to observations that result in identification of shortcomings in the data and the integration processes involved, which when corrected should improve model forecasts.

The NWM uses model elements based on a combination of 1000 m and 250 m grid cells and NHDPlus catchments and reaches that are referred to as the Hydrofabric. This is a complicated meshing of different data sources and scales that, notwithstanding how well processes may be represented, can impact the results. Hillslope hydrology processes may be poorly captured by 250 m grid cells and subgrid variability (variability at scales smaller than model elements) of processes may not be accounted for (e.g. infiltration, snow). Irregularity in the length of NHDPlus reaches, and catchment sizes has been identified as a shortcoming of this dataset that could be improved and would benefit HAND-based inundation modeling and likely other processes too (e.g. Garousi-Nejad et al., 2019). I think there should be consideration given to using catchment based model elements throughout the NWM rather than the 1000 m or 250 m grid currently used. Model "columns" should be catchments or hillslopes and the translation from grid to catchment polygon occur at the atmosphere to surface interface, rather than the runoff to streamflow interface as appears to be the current case. This would also open the model to many other catchment style models that are common in hydrologic research (e.g. TOPMODEL, PRMS, Sacramento, SWAT).

Data should also be used more in the NWM to update model states—the process of data assimilation. There has been considerable research in data assimilation for hydrologic modeling (e.g. Clark et al., 2008; Franz et al., 2003; Pathiraja et al., 2016; Gichamo and Tarboton, 2019). As I understand it, the current NWM only uses a fairly rudimentary nudging to update streamflow states. Effort should go into updating other model states using more formal data assimilation methods, such as the Kalman filter and its variants. Streamflow is driven by processes such as snowmelt and soil moisture drainage, so streamflow observations provide information on these processes, which through an assimilation process have the potential to be updated to yield better forecasts. There are also opportunities to use more available data to improve the model, e.g. from crowd sourced snow observations (http://communitysnowobs.org/). There is also an opportunity to identify states and processes in the model that are not presently well measured and pursue new measurements that may quantify these states.

Improving the representation of model component processes

Focus on component process representations is the approach used in much research hydrologic modeling. The research community continues to strive to obtain the physically correct, or proper representation of the physical processes involved. These include processes such as infiltration, runoff generation, evapotranspiration, snowmelt, subsurface flow and so on. Much of the NWM evolution since its first version was released has been on process parameterization. Process parameterization is also where the model gets criticized, because the choices are not believed to be right. While clearly this work should continue, I think the question needs to be asked, as to how much has been gained from process improvement work. Metrics presented to the committee reported improvement from 0.4 to 0.5. To me, this suggests possibly diminishing returns. It is with recognition of this, that I offered these process improvement suggestions after improvements due to more and better data, and data assimilation, which I personally feel may have better bang for the buck in model improvement.

In improving the representation of physical processes in the NWM, I think the following needs to be considered

- Develop an error budget to identify biggest shortcomings and help prioritize improvements. Identify sources of error and strive to attribute them to different causes or process representation deficiencies. Systematic sensitivity analysis (e.g. SUMMA Clark et al., 2015) may be a helpful approach here. Then with deficiencies and sensitivities understood, the priorities for model improvement may become naturally apparent.
- Address subgrid variability. The scale of hydrologic processes represented in the NWM (and many hydrologic models) is often larger than the scale of the processes involved. Variable quantities should be represented using some sort of distribution (VIC does this, Sacramento model does this, TOPMODEL does this)
- Address process realism
    - Assimilate the knowledge of field researchers who focus on concepts of preferential flow, residence times, old vs new water
    - There are many physically based models for infiltration and runoff generation (Infiltration vs sat excess) and these should be considered over the empirical (and frowned upon) curve number approach reportedly used in the NWM.
    - Use the best from other models (TOPMODEL, VIC, PRMS, Sacramento, …)
    - Field researchers would often state that overland flow rare except in built environments and agricultural fields. NWM reliance on overland flow at a 250 m grid cell scale deviates from these observations.
    - NWM uses trapezoidal channels, that are rare except in engineered environments
- Address altered and managed lands
    - Urban landscape
    - Irrigation, drainage and return flow
    - Consumptive use (Open ET)
    - Reservoir operations
- Address scale
    - Slope evaluated at a 1000 m or 250 m grid scale is biased low and this will affect snowmelt, infiltration and other slope dependent processes no matter how correct the process representation is.

- At the hillslope scale processes of run-on and convergence of flow into rivulets differs from the concepts of sheet flow used with a 250 m grid.

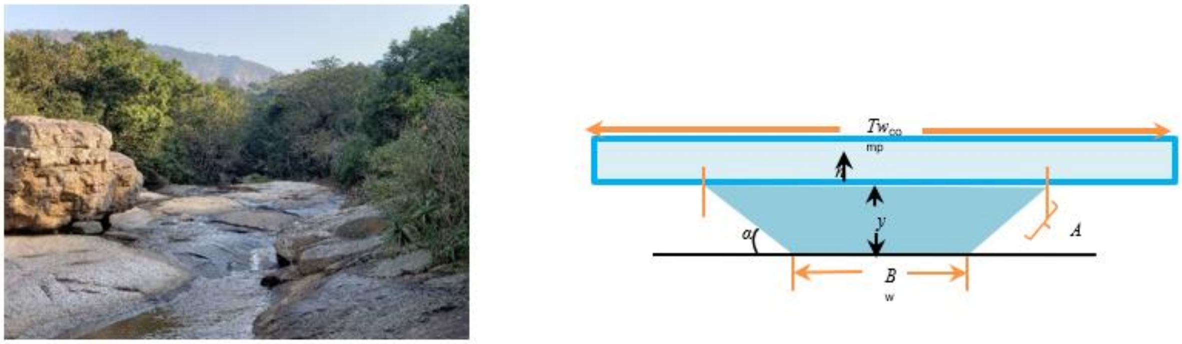


Figure 2. A natural river (left) versus trapezoidal and planar representation with 7 parameters suggested for NWM channel representation (right).

Figure 2 juxtaposes the channel parameterization suggested for the NWM with a real river. While trapezoidal and planar approaches are amenable to computation they are often poor representations of reality. A suitable compromise may be reach averaged hydraulic properties derived from high resolution topography or bathymetry following the approach of Zheng et al. (2018). With suitable refinement of the underlying hydrofabric (reach lengths and catchments) this approach may offer a route to bring measured hydraulic geometry into the NWM hydraulic routing.

To achieve improvements from changing process representations, I think it is going to be necessary to bring in more wholesale changes that address the considerations above. Tweaking NOAH-MP representations is yielding diminishing returns. But there may be bigger improvements possible from alternative process representations such as are used in other hydrologic models, more highly regarded in the hydrologic community (e.g. TOPMODEL, VIC, PRMS, SWAT).

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Biography: *David Tarboton is Director of the Utah Water Research Laboratory and professor of Civil and Environmental Engineering at 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 30 years and teaches Hydrology and Geographic Information Systems in Water Resources (david dot tarboton at usu dot edu).*

Ahmad Tavakoly - U.S. Army Corps of Engineers (USACE)

Recommendations and observations:

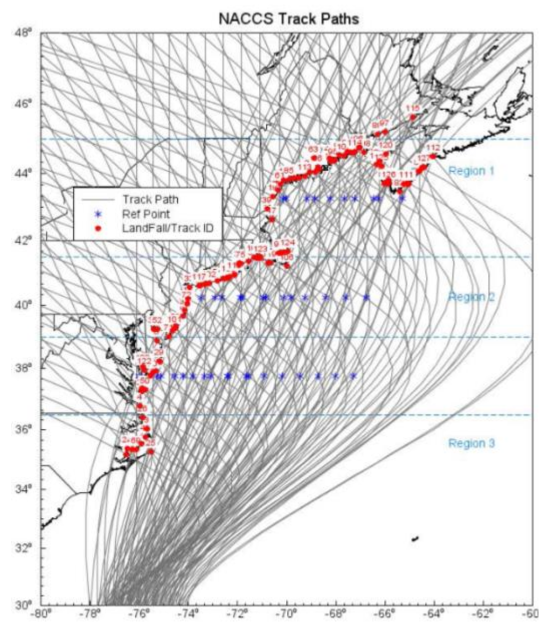
Tavakoly suggested three topics for collaborations and improvement of the National Water Model (NWM):

- Standard Operating Procedures for Flood Events

USACE also provides inland flooding and coastal storm surge information associated with various assigned missions. Leveraging USACE and NWC activities in a systematic way prior to, and during emergency flood events can save lives and property. A standard operating procedure (SOP) provides the guidance on how the NWC and USACE can collaborate before, during, and after a flood event. The Corps needs to have a full understanding of compound hydrologic loadings and other risks to water infrastructure, not only during synchronous flood events, but also for engineering design in a non-stationary climate, e.g. MVD study. The Corps also needs to identify impacts to navigation and public services and provide sediment budgeting for dredging operations.

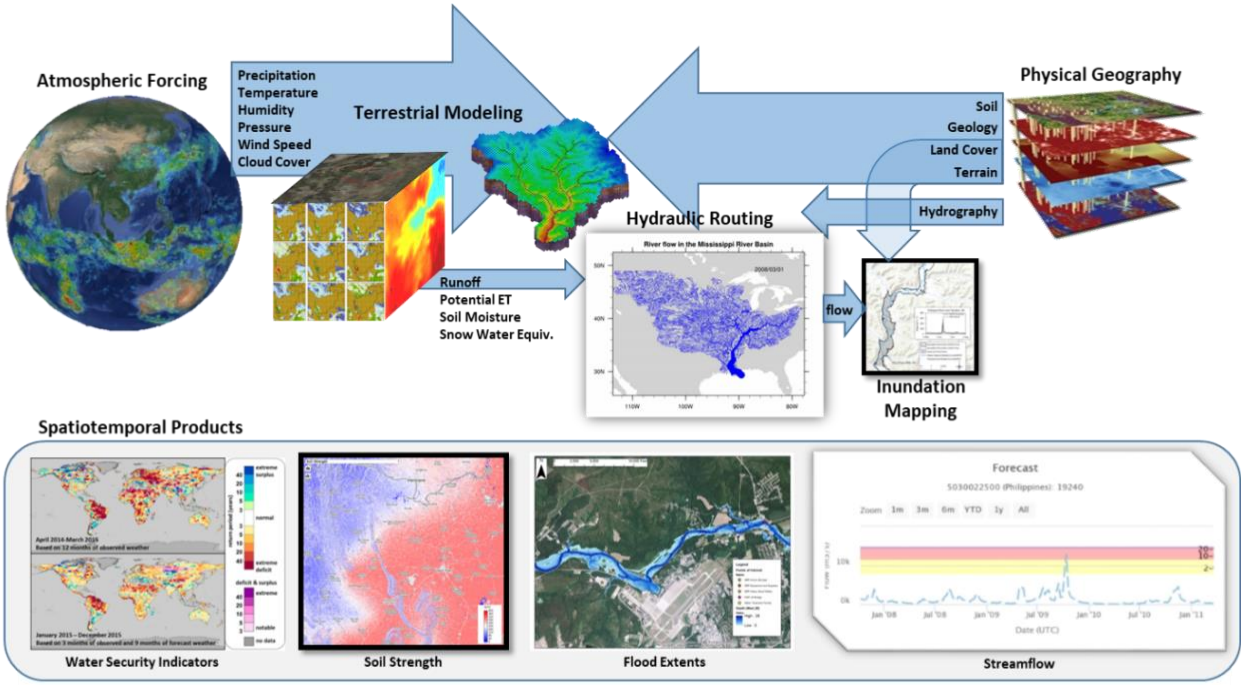
- Coastal and Inland Hazards System: Compound Flooding Hazard System (CFHS)

USACE-Coastal Hydraulics Laboratory (CHL) developed a probabilistic coastal hazard assessment (PCHA) known as the Coastal Hazards System (CHS). CHS leverages USACE regional coastal studies; historical measurements and high-fidelity climate, surge, and wave modeling results, creating a national storm database. An Inland Hazard System (IHS) is needed to support both USACE and NWS for riverine flood events, including linkage to the coast. Recent hurricane events such as Harvey (2017) and Florence (2018) necessitate the coupling of coastal and inland operational systems. Compound Flooding Hazard System (CFHS) could be considered to support both USACE and NWS for flood events, including linkage to the coast.



- An intergradation of concurrent drivers of multi-scenario flooding

An integration of systems is needed to include pluvial, fluvial, and coastal processes along with rain-on-snow events.



Biography: Dr. Ahmad Tavakoly is a Research Hydraulic Engineer in the Coastal and Hydraulic Laboratory (CHL) of the U.S. Army Corps of Engineers (USACE). He has been at the forefront of modernizing and expanding hydrology programs within the Coastal and Hydraulics Laboratory. Dr. Tavakoly's work in the area of continental-scale river flow modeling has been a cornerstone in the field of hydrologic science. He has been a team member of the Stream Prediction Tool (SPT) project. This new capability positions data providers to furnish more timely hydrologic information in data sparse areas. He earned a Ph.D. from the University of Texas at Austin in Civil and Environmental Engineering and a Master and Bachelor of Science degrees from Iran in Hydraulic Structures.

Michelle Thawley - Environmental Protection Agency

Recommendations and observations:

Thawley expressed her appreciation for filling in for Dwane Young at this meeting. She elaborated on the further development of *NHDPlus HR* generalization (hydrofabric):

- Input pruned network (points of interest)
- Output generalized and fully connected network. EPA is developing a tool that allows use of these points of interest and aggregated (white paper forthcoming)
- All generalized products maintain direct linkage to NHDPlus HR
- Open source tool

NHDPlus MR V3.0
EPA needs a medium-resolution product; you might take the high resolution version to use as a backbone; but there are disconnections. One cannot use high resolution NHDPlus as a geo fabric. There is no plan for a new version at this point. EPA hopes to have version 3.0 released in late 2019 or early 2020. It will eliminate the small catchment problems.

Thawley suggested that the *Internet of Water initiative may be a resource to explore* for the committee and OWP. It seeks to be a digital network of collective data from all sources, large and small, that would be compiled and managed in a national database accessible by all data users. (History: Aspen Institute Energy and Environment Program; Nicholas Institute for Environmental Policy Solutions at Duke University; Redstone Strategy Group). The goal is to develop common tools for achieving federated discovery, sharing and exchange of water data across regions and sectors; creation of common resources among data producers and hubs to make water data open and fair; development of a marketing, advocacy, and communications strategy.

Biography: *Michelle (Shelly) Thawley is currently an EPA project manager in charge of coordinating NHDPlus program activities within the EPA's Office of Water. Previously, Shelly worked in the EPA's Office of Pesticide Programs, where she developed an NHDPlus-based modeling environment for nationwide watershed scale water quality modeling efforts. She has a B.S. in Cartography and an M.S. in Physical Geography from the University of Maryland, College* Park (*thawley dot michelle at epa dot gov*).

Conclusion and Recommendations

The CAC-WP meeting accomplished a very great deal in terms of interagency dialogue and advancing collective understanding about both operational and community-centered future needs. Common agreement on priority recommendations included:

1. Articulation of requirements for further development of the NWM; articulation and communication of process, procedures, and definition for areas for potential community contribution.
2. Emphasis on improvement for observational data and potential sources of data.
3. Emphasis on improving data assimilation techniques and processes. Conduct gaps analysis of NWM operations for identification of areas that could benefit from more observations (e.g., data assimilation).
4. Stand up a community development engagement process, governance, and center; pursue proven mechanisms for community adoption:
    a. Development of sustaining communication and dissemination activity to advance understanding of the NWM, its operational priorities, and the creation of an infrastructure and connective tissue for a developmental R&D instantiation.
    b. Foster community participation via an AGU Chapman Conference convening or other opportunities for sustained interaction between the academic research and development community and the NWM.
    c. Develop guidelines for interaction; make public a software roadmap and development plan for the NWM; establish metadata and quality control.
    d. Strengthen more formal partnerships with the private sector.

Agency and organizational views

FEMA representatives emphasized collaboratively and creatively developing techniques together to advance the NWM, and how routinizing necessary deliverables might be accomplished, with emphasis on the criticality of the OWP mission to FEMA: "*Without NWM we have nothing.*"

Private industry contractors expressed deep appreciation for their involvement in the meeting and enthusiasm and desire for participation in expanding NWM capability.

NCAR representatives noted there is much more that needs to be done for an operational model that has high demands and high application possibilities. We must increase efforts to support people at academic levels, at user levels, and articulate the real needs that can advance the system and the science to support a viable operational system at the same time. NCAR provision of forcing data is another contribution that can help advance the work.

EPA: Improving connection to this committee and to these conversations is important to EPA, whether in providing support in improvements, or providing value-added products. A more direct dialog is desired and would be productive.

NOAA: NWM work is a very target-rich environment, with great possibilities to advance prediction capability. The progress made thus far enables more progress. Some of the goals of this effort align with some of the highest goals of the agency. This meeting has advanced understanding of how to better serve OWP and the NWC. Involvement with the Joint Center for Satellite Data Assimilation (JCSDA) is necessary to advance DA capability, and to continue to leverage the connections there that already exist.

OWP: Priorities from these discussions are to continue to lower the bar to entry for collaborative development of the model; to get the community engaged sooner rather than later, and how best to enable building that base. OWP will continue to work with IWRSS partners to make sure efforts are fully coordinated. From an OWP perspective, this meeting has been very beneficial.

USGS: Taking a long view for the future is important, and ensuring that we continue to grow. Taking all the recommendations heard in these discussions, we have to build this effort as a community effort, it has to be larger than operations alone. That is a metamorphosis into another phase for the OWP and the NWC. We are at a turning point. We need the community input, and federal agency input. We need to map out long-term outlook, shape direction, and bring it back to this group.

USACE/ERDC (Engineer Research Development Center)**:** An understanding of the constantly changing physical environment is critical for the Army at both the tactical and strategic level. Commanders routinely use environmental information to identify constraints imposed by the terrain for humanitarian assistance/disaster response efforts and when preparing the battlespace. ERDC has, with support from the Army, Air Force, and the U.S. Marine Corps, along with academic collaborators, maintained and developed a framework for delivering quick flood forecasting and streamflow simulation to generate flood inundation maps at a continental scale using globally available datasets. This framework, known as the Streamflow Prediction Tool (SPT), is applied globally. SPT provides timely and actionable hydrologic information (i.e. 15-day streamflow forecasts) at the continental scale for each river, stream, and tributary. Interaction and collaboration between USACE-ERDC and NWC are inevitable due to the similarity between their missions to respond to natural disasters such as floods. Ahmad Tavakoly, representing USACE, expressed appreciation for participation in the meeting and the desire to continue to be involved in discussions and development for the National Water Model and community engagement activity.

NWC: We have to evolve and change as an organization; and evolve and change the way we do things. The only way to be successful is to tackle a second phase of development of the NWM. We cannot do this alone. We cannot achieve that phase 2 unless we have an engaged community, whether in this location, physically, or virtually. The dialog was very enriching, and has helped focus our vision on both near and long term.

The meeting was both productive and rewarding in helping the CAC-WP Committee and the OWP to think about and advance an intellectual model of how to collectively do things relating to development cycles, procedure, and requirements, and in creating viable community development. The group, in effect, is developing *a discipline of national water modeling*. There may be utility in continued conversation of the break-out groups—creating and utilizing mechanisms for ongoing dialogue, and laying out a longer term view, focused by the needs of the NWC, will be essential.

The strength and depth of the CAC-WP Committee in its broad and experienced representation across both research and operational backgrounds, with both a cross-agency, and cross-disciplinary approach, is fundamental to future water prediction capability and emergency management.