National Water Hazards & Vulnerabilities: Improved Forecasting for Response & Mitigation

Statement of

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Good Morning Chairman Shelby and Ranking Member Shaheen, and members of the subcommittee. I am Dr. Tony Busalacchi, President of the University Corporation for Atmospheric Research, and recently elected member of the National Academy of Engineering. UCAR is a nonprofit consortium of 110 member universities granting degrees in atmospheric and related earth sciences. UCAR's primary activity is managing, on behalf of the National Science Foundation, the National Center for Atmospheric Research (NCAR). In addition, UCAR manages a suite of programs (UCAR Community Programs) that provide service and support to the academic community.

NCAR is a Federally Funded Research and Development Center with over 600 scientists and engineers conducting weather, water, climate, air quality, and space weather research. Staff also manage supercomputers, research aircraft, and Earth observing systems available as a resource to the nation's research community. Our UCAR member universities and staff scientists conduct research for use by government agencies and the private sector. We aim to further the understanding of atmospheric and related phenomena and help create more accurate environmental forecasts that protect lives and property, spur economic growth, support the national defense, and enhance our quality of life.

Prior to becoming the UCAR President, on August 1, 2016, I served as Director of the Earth System Science Interdisciplinary Center and Professor of Atmospheric and Oceanic Science at the University of Maryland. Before my time at the University of Maryland I was a civil servant for 18 years at the NASA Goddard Space Flight Center (GSFC), the last 10 years of which I was a chief of the Laboratory for Hydrospheric Processes and member of the Senior Executive Service.

Let me begin first by thanking you Mr. Chairman for your strong support of science in particular with respect to your vision on the topic of this hearing, as well as all the members on this committee. During my 34 years working in Maryland and now at UCAR I have observed the tremendous support this committee has provided for the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Institute for Standards and Technology (NIST), and the National Aeronautical and Space Administration (NASA), as well as for the university research communities that collaborate with these agencies.

There can be no doubt that science and the resulting societal benefit from these agencies and universities has enhanced our quality of life while contributing to both economic and national security. Much of the work we do at UCAR and NCAR would not be possible without robust funding for the Geosciences directorate at NSF and many of the successes you hear today are the result of past funding that enabled the science. Moreover, the topic of today's hearing on water is one that fits exactly in the nexus of scientific and social understanding that supports economic development and national security so thank you for inviting me to testify on this very timely subject.

Following the suggestion in the committee's letter inviting me to testify, I will organize my testimony around the following questions that I believe are critical in examining the "water nexus":

1. What constitutes the current state of the nation's water enterprise?

2. What is the desired future state of the nation's water enterprise?

3. What are the gaps that need to be addressed to get to the desired future state?

4. What processes and policies are needed to identify roles and responsibilities? What, if any, are the next steps for Congress?

I will highlight the areas where the water nexus can best provide value to the taxpayer and where impacts can best be made. I will also discuss how this is an area where we have seen one of the most significant research to operations (R2O) transfers in our nation's history and it demonstrates how the research and operations communities collaboratively addressed a hard problem that has tremendous benefit to all American taxpayers.

1. **What constitutes the current state of the nation's water enterprise?**

Today's water enterprise is a triumvirate that consists of academia, the public sector and the private sector. The government's traditional role within this triumvirate is the protection of life and property; the building and management of both small and large infrastructure; and the enhancement of national security through the issuance of forecasts for severe weather to include floods, droughts and anything water related. The private sector's traditional role is to create customized and tailored hydrologic products and services to a broad customer base of private individuals and businesses in a multitude of sectors. The academic and research community, including federal laboratories and centers, works to improve our common understanding of the Earth System and improve operational products. The three work together, often in a public-private partnership, to advance synergistically our knowledge and operational capabilities.

We must also acknowledge that the growth of private sector products and services in the water enterprise has benefitted from public investment both in providing foundational observational data and observing networks, and in creating open community models which have enabled companies to quickly make new products that have hydrologic applications – not just in the United States, but around the world. This approach has provided an incalculable return on investment of public tax dollars and goes largely unnoticed even as we all recognize that the protection of life and property is paramount.

Now is an extremely exciting time in the world of water. The investments over several decades have led to advances in science and technology such that the US is poised to make a leap forward in our understanding of weather, climate and water through modeling, monitoring, and forecasting. These advances include the development of new and more complex models of the land surface and, more broadly, the Earth System; vastly improved weather predictions that help us estimate weather and water risk; expanding resources for supercomputing and communications; and new statistical techniques to enhance the skill of streamflow forecasts. NCAR is collaborating with federal agencies such as NOAA, NASA, DOI and DOD to integrate these advances into tools and services that will deliver far more information to water sector entities than has been possible before.

A key example of this collaboration in the water enterprise is the new National Water Model (NWM), which was recently operationalized by the National Weather Service at the National Water Center in Tuscaloosa, Alabama. The implementation of this forecast tool could not be more timely given the serious flood catastrophes in 2016 as we saw in Baton Rouge, La, Ellicott City, MD, and Kanawha County, WV. The NWM generates hydrologic (streamflow) forecast outputs in real time for an unprecedentedly comprehensive collection of the nation's rivers and streams – 2.7 million total locations for prediction. This detailed information from the NWM provides a significant complement to the existing operational streamflow forecasting service, which previously relied solely on simpler models and techniques to forecast for thousands of critical locations. These forecasts are vital for the operation of the nation's water infrastructure, supporting hydropower, agriculture, navigation, recreation and other purposes, and informing emergency management during floods and droughts with vital watch, warning and outlook products. The initial deployment of the NWM is a major new direction for the water enterprise, and one that has enormous future potential to augment the value of the traditional forecasting services, with broad economic and social benefits. Achieving this full potential will depend on the success of continued investments and progress toward resolving long-standing scientific and observational challenges in water prediction.

The National Water Model's history begins with the initial investment in basic research by the National Science Foundation to develop a regional weather research forecast (WRF) tool at NCAR. WRF was developed in an open-platform, open-access community manner that ensured that anyone who wants to utilize it to test forecasting hypotheses, to tune it to specific phenomena, or privatize could easily do so without charge or clearance. WRF's developers also ensured that it was highly adaptable and portable, so researchers could use it as the foundation for forecasting systems that could predict a wide variety of environmental phenomena. Indeed, since WRF's creation, researchers from academia, government and industry have created WRF-Chem, Hurricane WRF, WRF-Crop, WRF-Fire, and many others.

One such WRF spin-off is WRF-Hydro, which has connected hydrological forecasting with weather forecasting. WRF-Hydro is an excellent example of the triumvirate across academia, the public sector and the private sector as the initial investment by the NSF was leveraged with contributions by mission oriented agencies such as NOAA, NASA, and the USGS together with a partnership with the private sector in the form of Barron Weather Services. This model enabled the utilization of a vast array of environmental observations – from stream gauges to satellites – to provide an initial capability to forecast the flow of a region's rivers and streams, the moisture of its soil, and the quantity and type of precipitation. Initial testing of this model in Colorado during the anomalous flooding events of 2013 demonstrated several of the model's strengths over conventional flood forecasting methods. Working with Barron Weather Services of Huntsville, AL, NCAR scientists then applied the model for further testing and operationalization in Romania. Later, the nation of Israel collaborated with NCAR to implement their own version of WRF-Hydro for operational hydrologic prediction. The success of the model's implementation in these two countries led NOAA to pursue utilizing elements of WRF-Hydro as the basis for the National Water Model, following several rounds of improvements, testing, and integration with existing weather forecasting systems.

The development and implementation of this model from research to operations could not have happened without sustained collaborative engagements between academia, industry, and government. The implementation has already proved useful in the provision of flood forecasting associated with several anomalous events – including a Hurricane landfall in North Carolina last year and the more recent flood events in California this winter. I should also add that NCAR delivered the model two years ahead of schedule and on budget.

The model's implementation has identified several new and exciting research questions for the academic community to pursue, including the improvement of quantitative precipitation forecasts to enhance our capacity to predict rapidly changing flood inundation conditions. Knowing how much, when, and where precipitation will fall is a vexing question and a critical one to answer in order to improve flood forecasting and water resource management more generally.

The model's implementation has also created several new and exciting opportunities for industry, with the prospect of broadcast hydrology on the horizon. Imagine turning on the nightly news and getting not just a weather forecast, but also street level visualization of river and stream forecasts. Such services could be highly valuable not just to private citizens and small businesses, but also emergency managers. Such services could also be provided abroad, providing benefits to citizens of other nations who struggle to manage their water issues.

Such predictive models are only as good as the observations that go into them. In the past three years, NASA and NOAA have launched three satellites that have been vital in improving water forecasting and services. In 2014, NASA and the Japanese Aerospace Exploration Agency (JAXA) launched the Global Precipitation Measurement (GPM) satellite, which provides next-generation observations of rain and snow worldwide every three hours. The GPM mission contributes to advancing our understanding of Earth's water and energy cycles and improves the forecasting of extreme events that cause natural disasters. GPM applications include extended capabilities in monitoring and predicting hurricanes; enhanced prediction skills for weather and climate; improved forecasting capabilities for floods, droughts, and landslides; better agricultural crop forecasting; and the monitoring of freshwater resources.

In 2015, NASA launched the Soil Moisture Active Passive (SMAP) satellite, which provides measurements of the land surface soil moisture and freeze-thaw state with near global coverage. SMAP measurements coupled with hydrologic models can determine soil moisture conditions in the root zone, which enables forecasters to better understand water and energy fluxes at the land surface and improve flood prediction and drought monitoring.

Most recently, in 2016, NOAA and NASA launched the Geostationary Operational Environmental Satellite – R Series (GOES-R, now GOES-16 since launch and operationalization). GOES-16 provides weather pattern images every 30 seconds, providing more accurate and timely information on severe storms from space than ever before. Additionally, GOES-16's Geostationary Lightning Mapper instrument can detect the presence of lightning, providing forecasters with the ability to focus on developing extreme weather and before storms produce precipitation.

In addition to overhead observations, real-time stream gauges from the United States Geological Survey (USGS) and other agencies are also critical to the modeling effort. The USGS, in partnership with many state, local, and tribal entities, provides a backbone of both surface and underground water information, all of which can directly feed into national forecasting systems and improve model performance.

Scientific understanding of the water cycle and its interconnectedness with the Earth system underpins activities across many federal agencies. The U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Department of Energy now use the latest in atmosphere-hydrology modeling to understand risks to water security. A critical emerging capability is continental-domain hydrologic modeling, where the latest hydrologic models can now produce realistic estimates of weather and climate risk over large geographical domains. These advances enable water agencies to develop coherent strategies to modernize and maintain their infrastructure investments.

Water security is clearly of global importance. We have recently seen how droughts are the catalyst for migration and regional instability, motivating the need for new understanding of water security in different corners of the globe. The recent community efforts in Earth System modeling capabilities have resulted in incredible advances in global hydrologic modeling. In one recent example, NCAR's Community Earth System Model was used to simulate the limited water availability in Iran. There is currently a strong collaboration between NCAR and the university community (led by the Consortium for the Advancement of Hydrologic Science Inc.) to substantially advance global hydrologic modeling capabilities. The effort focuses on integrating scientific understanding and modeling capacity developed by different groups working around the world in order to improve simulations of hydrology worldwide.

Although the water enterprise has a long history of integrating advances in science, technology and engineering for the betterment and protection of society, it is currently undergoing a major transformation through leveraging these new datasets, models, and computational resources. This transformation is exciting and will, with continued investment, lead to major gains in capability that benefit the United States on many fronts. I truly believe these are gains that the public will be able to readily grasp. At present, we have a new modeling approach that shows enormous potential in forecasting events that affect life and property.

Looking over the horizon, there are capabilities we will want to obtain in a future state that will better enhance economic and national security. Needless to say, given the scarcity of water, it is incumbent for us to move towards this future state as rapidly as possible.

2. **What is the desired future state of the nation's water enterprise?**

Better understanding of water requires an appreciation by society of its intrinsic value and its inter-connected nature to other events. Thus, an Earth system approach that encompasses more than just water should shape our thinking. I believe that sub-seasonal (2 weeks) to seasonal (3 months) forecasts are the sweet-spot the scientific community should aim to improve to build a generation of operational water products that empower our society to better manage water resources. Such forecasts, however, are only possible by considering the entire earth system as whole as Sub-seasonal to Seasonal (S2S) forecasts are driven by global factors such as the pattern of sea surface temperature in the Pacific and Atlantic. These sea surface patterns, in turn, drive tropical thunderstorms that can drive weather patterns over the U.S. causing floods and drought. While the research community has established this connection, the creation of a reliable S2S forecasting system based on this knowledge of ocean-atmosphere coupling is in its infancy and requires a significant research investment.

In times of drought, particularly in the Western US, water resource managers rely heavily on the ability to predict conditions at seasonal time scales – that is, looking three months ahead, or even further – as they need to know the likely snowmelt runoff volume that can be expected to refill reservoirs in the spring. These managers need to anticipate their long-term ability to provide water for agriculture, hydropower, the environment, and the needs of the populations of major cities. Seasonal streamflow forecasts are likely the most economically valuable water prediction in the western US, which the allocation and management of billions of dollars' worth of water depend. Recently, sub-seasonal forecasting for shorter periods, such as looking out 3 and 4 weeks ahead, or beyond this to the following month, has emerged as a major focus of scientific and operational research. Reservoir release decisions can be made based on sub-seasonal information that lead to water savings and better economic decision making about water supplies for a range of customers each year. NCAR is working with NOAA, USACE and the Bureau of Reclamation to find the best ways to harness sub-seasonal weather predictability and develop new information products for the water sector, including ensemble atmospheric and streamflow predictions at the watershed scale, looking ahead for weeks to seasons.

Ensemble methods are a computationally intensive strategy for getting a handle on uncertainties in simulating weather, climate and water. Because all of our models and datasets are not perfect, scientists and forecaster work to quantify forecast errors by running them many times rather than just once, each time with slight variations that represent possible errors in our data and models. This gives a forecaster a basis for telling a decision-maker the confidence of the forecast – including the risk that it may be wrong, or that it may exceed a critical threshold, such as a levee elevation. Along with improving model resolutions, ensemble methods are a major strategy through which weather, climate, and water modeling agencies around the world are seeking to upgrade the value of the information that can be provided to decision makers. NCAR has developed real-time ensemble forecasting capabilities for a number of USACE and Reclamation reservoirs, some of which are now helping to guide the development of decision approaches for better management of water resources in the face of weather and climate variability that leads to extremes such as floods and droughts.

The state of hydrologic forecasting and the enterprise that supports it should progress in a similar fashion as the weather enterprise – particularly in the development of the private sector. Currently, private weather companies provide tailored, visualized, and broadcast weather forecasts for private individuals and businesses. This capability is built on the foundation of strong government and academic observations and modeling. New developments like the National Water Model and the success of National Integrated Drought Information System (NIDIS) help to show that we are now on the verge of rapid development of forecasting abilities for water and related issues. When these modeling and monitoring systems are as robust as weather observations and models, then we can expect a similar rapid development of the hydrologic services industry. Several industry sectors would seek such services – energy, agriculture, fishing, shipping, recreation, tourism, etc. Additionally, private citizens living near rivers and streams would pull up applications and websites to get real-time hydrologic information and forecasts at their specific locations of interest. As the hydrologic industry strengthens, more well-paying private sector job opportunities will manifest, companies will manage their operations more effectively and efficiently (meaning more profits for shareholders, more opportunities for export, and better prices for customers), and private citizens will mitigate risks to themselves and their property.

Efforts such as the National Water Model provide a compelling example of the future development of academic research into the coupled nature of hydrology and other earth systems. The NWM also provides useful insights into Operations-to-Research pipeline activities – given that researchers have long been intrigued by the scientific questions raised when a research model becomes operational. When an operational prediction model confronts observations on a 24/7 basis, the research community is presented with a wealth of information as why a forecast is successful and when it is not. Research fields are emerging from these early advances in a variety of areas such as improving streamflow forecasts relevant to managed water systems, coupled freshwater-atmosphere modeling, and coupled freshwater-ocean modeling. Interdisciplinary science between hydrology and soil science, land use, geography, and other fields could are also emerging as opportunities for new research and, eventually, applications.

3. What are the gaps that need to be addressed to get to the desired future state?

A host of improved water cycle observing capabilities are needed to accelerate our predictive capacity for hydrology. These measurement platforms include expanded space-borne and ground radar estimates of precipitation, expanded high altitude Unmanned Aerial Vehicle operations for very high resolution measurement of snowpack, glaciers and flood inundation in near real-time or as events, expanded groundwater observing and monitoring networks and significantly expanded streamflow measurement networks. Each of these measurements provide critical hydrologic characterization information that quantifies where water exists on and within the land. Utilizing our modern communications capabilities in combination with scientific innovation we can ingest these critical observations into a new generation of water forecasting tools thereby improving model forecast accuracy and timeliness.

The underlying hydrologic modeling systems themselves are already undergoing rapid transformation, moving from fairly simple place based models, to highly detailed descriptions of water moving on and through the Earth's landscape, including its interactions with human infrastructure. However, we are only just beginning to quantify and realize the potential we have for transforming this information into actionable forecasts. Significant work remains in linking together the different components of the Earth System in these models, in particular, the ways in which we quantify the impact humans have on hydrologic processes. Improved descriptions of groundwater systems, snowpack, precipitation forecasting, flood inundation and vegetation water use all remain as critical focus areas. The methods in which we ingest or 'assimilate' observational data into these models remains a key challenge for many forecast systems and, finally, our models must always have the capacity to evolve as changing landscape conditions and changing water management practices continue to drive real change in local and regional hydrologic cycles.

This new generation of computer models, like the National Water Model, are both data intensive and computationally intensive. They are designed to model the continuum of water from the highest peaks to the ocean shores and do so with ever increasing spatial fidelity. Like an early, grainy digital photograph which now has become crystal sharp and lifelike, these models continue to improve their spatial resolution which creates an enormous need for high performance computing. Also, like early digital cameras, the computers of today will simply not be adequate or acceptable in a few years' time to meet the challenge of predicting "water everywhere, all the time." These new computing systems will push the 'Petaflop' horizon and will also create new challenges and opportunities in data transmission to get critical information from centralized computing centers out to the public and to the private sector where its value can be realized. Already, data from platforms like the national radar network and, soon, the National Water Model will be ubiquitously available from cloud internet services. This creates enormous opportunities for private sector capital investment and revenue potential in addition to the basic goal of saving lives and property. In short, there is now and will continue to be a "flood" of hydrologic information and the public-private-academic water enterprise stands at the crossroads of meeting societies water needs and opportunities.

To create better Quantitative Precipitation Forecasts, more work needs to be done to better understand the interplay between soil moisture and water vapor, a better monitoring of the water vapor in the atmosphere in features such as atmospheric rivers, and better modelling at higher resolution scales that resolves convection in a more accurate manner. Research funding to pursue the scientific understanding will make us more aware of the earth's interconnected systems, instrumentation funding for remotely sensed and in situ observations will better monitor the earth's water, and investments in computing, data assimilation, and science will yield better models.

Understanding the atmosphere-ocean connection and modelling it well will enhance various water forecasting tools. An opportunity to leverage the advances made possible by the National Water Model is better coastal forecasting so that approaches to predicting inland flooding can be merged with coastal flooding. 50% of America's population lives near the coast of an ocean or the Great Lakes. The blending of tidal, storm surge, and coastal inundation forecasts is in its nascent stage – and work has barely begun to couple these traditionally coastal forecasting tools with the National Water Model. The nation's estuaries are a source of great economic strength, and their utility is best realized when we can predict and understand ebb and flow anomalies. Further investments in updating these traditional ocean models to combine with the National Water Model would significantly improve the protection of life and property at the coasts, and provide for the security of US Naval, Coast Guard, and Merchant Marine installations. Atmospheric Rivers (AR's) – narrow bands of water vapor carried from the south pacific to the west coast – also significantly impact water conditions, particularly in California. Over the past year, these intense rain events have reversed the California drought, but have also caused localized flooding. Investments in better AR modelling will enable water resource managers to anticipate intense precipitation and manage reservoirs accordingly. Finally, weather events that initiate over the oceans – hurricanes, deep low pressure systems, and severe storms – are hard to predict partly because of the relative lack of in situ data sources. Sustained ocean observations at various depths and coordinates will enhance our ability to initialize models and assimilate good data into these models so that we can better predict weather events. All of these forecasting tools – coastal forecasts, AR forecasts, and other weather forecasts – are significantly improved through improved and sustained ocean observations.

4. **What processes and policies are needed to identify roles and responsibilities? What, if any, are the next steps for Congress?**

Clearly, the water enterprise relies on all three partners of the weather enterprise, that being, the public sector, the private sector and academia. What can Congress do to leverage the best hydrologic forecast at the least cost? What is the role of the public sector relative to the private sector? The real issue is what do we want this enterprise to look like 20 years from now at the national and international level?

U.S. leadership in water forecasting technology is essential. Other nations are already aggressively utilizing their foreign aid programs to market and deploy their water observation and prediction technology. Once in place those systems can create strong partnerships for decades in terms of technology and IT exchange. By not actively pursuing these applications with flagship U.S. technologies the U.S. will miss out on a host of water related development business opportunities. Water is both essential and a potential problem everywhere in the world and the nations with strong relationships on water and water infrastructure development are nations that have a common cause for strategic policy development. How nations use and share their water resources are inextricably tied to their fundamental views on fairness, freedom and opportunity.

On the near-term horizon, we see the need for investment in several observation, modeling, and computing activities to move the enterprise to the next step. We need more 'operational' satellite capabilities, but at an affordable cost. Several of the satellites I mentioned earlier are research grade, and do not meet data latency standards that are needed. Operational satellites should include constellations of low-earth orbiting platforms for improved precipitation measurement, improved land surface characterization through hyperspectral imagery, improved topographic profiling through laser altimetry and/or lidar based methods. Radar gaps in the western U.S. must be filled or supplemented by improved satellite, ground based, or airborne radar precipitation platforms. The water enterprise needs sustained support for advancing the use of data assimilation into all of our modeling systems, particularly hydrologic models, and in improving the spatial fidelity of those models. While various Earth System component modeling systems are beginning to be loosely connected, significant work remains in terms of making sure those coupled processes are completed with the accuracy and spatial resolution required for high value environmental prediction information. Finally, we have recently developed a set of potential compute requirements for the next four years for The National Water Model which will be nearly 10-fold from today's usage.

For better applications, the enterprise will need improved development of 'web mapping services' for the effective and efficient display and querying of geospatial data including weather and water forecasts. These new tools will form the backbone of environmental situational awareness, which synthesize not only weather and water forecast information but also information on human infrastructure, transportation, recreation, emergency response and economy. They will serve as the next generation of decision support tools which, like today's proximity sensors in cars, will provide decision makers and the public alike, information on hazards *before* they occur.

The Subcommittee should also seek to better connect research activities across the government with operational requirements at NOAA. Programs that support active and strategic research to operations pathways have been challenged in years past with fits and starts and ad hoc application. The success of the research to operations achievement in the development of the National Water Model should be replicated often, so as to bring the best science into water forecasting operations effectively and efficiently. Working across agencies can be difficult as well, as varying agency missions sometimes snag collective advancement towards specific goals. Offices with the funding and the wherewithal to ensure that research finds its way into operations will ensure that these successes are more common. I would also add that such activities should not be limited to government operations; indeed, many publicly funded research successes should more easily find their way into private sector solutions and applications. Finally, this pathway should be a two-way street. When scientists are tasked with research problems that are generated by an operational requirement, academics can directly participate in ensuring that society benefits.

Finally, I ask the committee to consider the institution of a decadal survey for the entire weather enterprise that would include water. The boundaries of operations have been driven by the science into new forecast areas, and the weather, water and climate enterprise needs to consider doing what we have done in the area of earth observations, and start planning over ten year periods. Prior to taking on my new position at UCAR, I served as the co-chair of the National Academies' Decadal Survey for Earth Science and Applications from Space and the roadmap it will provide will prove critical to NOAA, NASA and USGS. Given the implications of water and weather, I urge this committee to consider enacting into law a decadal survey for this community. The Board on Atmospheric Science and Climate at the National Academies is currently addressing the issue and there is wide spread recognition that with limited resources our community must present Congress and the Administration with priorities. A decadal process will allow us to prioritize what has to be done and do so in recognition of the current fiscal realities.