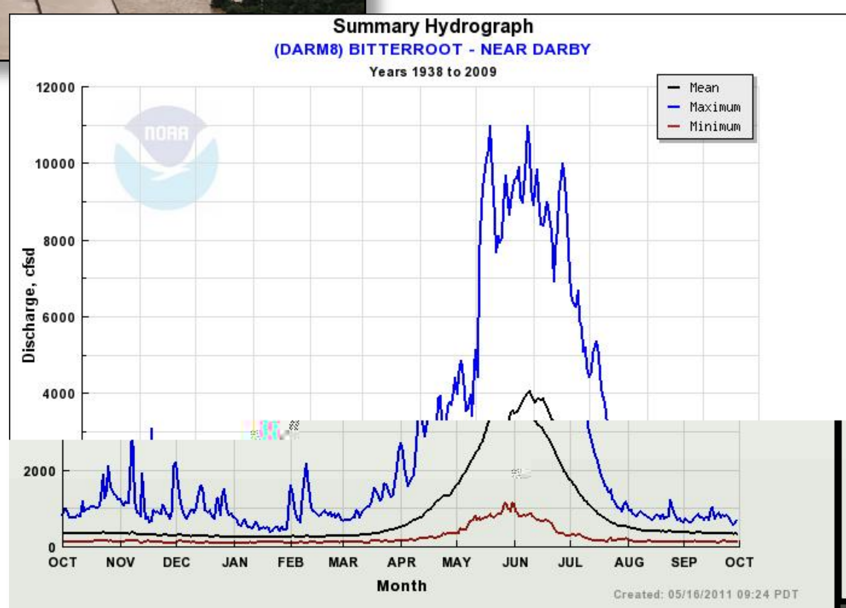
National Weather Service Water Industry Analysis Report

Findings on innovation in the private water industry

July 23, 2018



Cover Images: Interstate 10 flooding during 2017 Hurricane Harvey (Barclay, 2017) / Hydrograph of the Bitterroot River near Darby, Montana (Howell, 2011).

EXECUTIVE SUMMARY

In 2017, the National Weather Service (NWS) conducted a study to examine trends and innovations within the water industry[1]. The scope and scale of the study was limited to looking at the water services industry as related to the NWS's mission. This document details the findings and recommendations from this study.

NWS considers the water enterprise[2] as focusing on water forecasting with three main components: 1) monitoring and observations; 2) modeling and forecasting; and 3) service delivery. In addition to these components, a fourth broader component, the Business of Water, which considers how to foster a collaborative environment for advancing the state of the water enterprise, was also analyzed within the water industry as part of this study. To scope the effort, the study focused primarily on the U.S. private water industry component of the water enterprise, leaving aside the non-profit, academic, or international components. The goal was to uncover major trends and innovations occurring with the U.S. private water industry. Major findings, as well as recommendations from the private industry with regards to how NWS operates, are captured.

NWS Mission and Role

NWS has a dual mission – to provide observations, forecasts, and warnings of weather, water and climate for the protection of life and property *and* enhancement of the national economy. Operationally, NWS disseminates hydrologic forecasts through the River Forecast Centers (RFC) and disseminates flood forecasts and warnings through the Weather Forecast Offices (WFO).

NWS also includes the Office of Water Prediction (OWP) which researches, develops and delivers state-of-the-science national hydrologic analyses, forecast information, data, decision-support services and guidance to support and inform essential emergency services and water management decisions. In partnership with NWS national, regional, and local offices (e.g. River Forecast Centers, Weather Forecast Offices); the OWP coordinates, integrates and supports consistent water prediction activities from global to local levels. The OWP is designed to support a consistent and unified hydrologic program while maximizing efficient use of resources helping to ensure NWS excels as a science-based service organization.

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[1] Water industry defined here as private companies that provide observations, modeling and forecasting, or services for clients that need information or support related to water.
[2] Water enterprise defined as public sector, private industry, and academic institutions with a water focus.

Trends, Findings and Recommendations

This study found that technological innovations are occurring rapidly across the Water Industry. These include:

- Advances in sensor technologies;
- Increasing use of the Internet of Things and crowdsourcing for data collection and sensor sources;
- Widespread migration to cloud-based services and big data analytics;
- Introduction of larger and more complex modeling leading to more precise and refined results;
- Delivery of real-time services and alerting to mobile devices; and,
- Closer integration of water forecasting results into more sophisticated end-user applications, such as hyper-localized flood inundation mapping.

The private water industry is pushing the envelope on all of these fronts. Additionally, on the "business of water," there have been a number of recent studies, reports, and user engagements focused on how to advance the state of the water enterprise. Despite these advances, uncertainty exists in the private water industry with regard to how to position itself vis-a-vis current and emerging NWS products and services. NWS River Forecast Centers (RFCs) still provide the official river forecasts, while the recently introduced National Water Model (NWM), a continent-wide distributed hydrologic model, is considered guidance as it is still being vetted. With the introduction of the NWM, companies are wondering how their products and services can work collaboratively, as opposed to compete, with this new NWS capability. Despite this uncertainty, many companies still regard the forecasts coming from NWS as the validated standard and NWS data as key enablers for the overall enterprise.

Some key recommendations for NWS to consider include:

- Improved access to data across all systems;
- Support for multi-model ensemble modeling in all basins incorporating dams, reservoirs, and diversion data into the NWM;
- Processing of the large-scale data and provision of those results externally; and,
- More frequent engagement with water enterprise partners in both operational settings as well as strategically.

Outlook

With many significant, large trends underway, NWS will need to take a strategic perspective with respect to our roles and responsibilities within the larger water enterprise. The findings and recommendations identified in this report will act as input to a larger discussion for how NWS moves forward to enhance the water enterprise and to establish lasting partnerships with the private water industry.

1. INTRODUCTION

The mission of National Weather Service (NWS) is to "Provide weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy." Recently NWS's Office of Organizational Excellence (OOE) completed a *National Weather Service Enterprise Analysis Report* (NWS, 2017a) that reviewed innovations occurring in the private weather industry with goals of understanding how NWS could better partner with private industry and position itself going forward to leverage private industry innovations. This report extends that previous work by focusing on water, the second of the three NWS mission domains.

As NWS evolves in the face of change, we will need broader strategic thinking based on a deeper understanding of changes underway in the weather, water, and climate enterprise. Further, our stakeholders will benefit from NWS having a comprehensive strategic view of the future that new leadership can reference and build upon. Therefore, the timing is opportune for NWS to use the findings in this report on trends in the water enterprise, to communicate and act on a path forward to strategically engage with the broader enterprise.

The 2017 extreme hurricane events also provided a compelling reason for performing this work. With Hurricane Harvey alone dropping an historic 51.88 inches of rain in Texas, the accompanying massive flooding, and the estimated economic impacts at least totaling $70 billion and likely significantly more (Holmes, 2017), there is a clear need to advance the state of our water enterprise. Hurricane Harvey, however, appears to be part of a trend of an increasing number of billion dollar disaster type events (see Figure 1)[3]. NWS seeks to partner closely with private industry to make such advances and this report aims to identify such areas of innovation.

[3] Hurricane Harvey Assessment may be found at **https://www.weather.gov/media/publications/assessments/harvey6-18.pdf**.

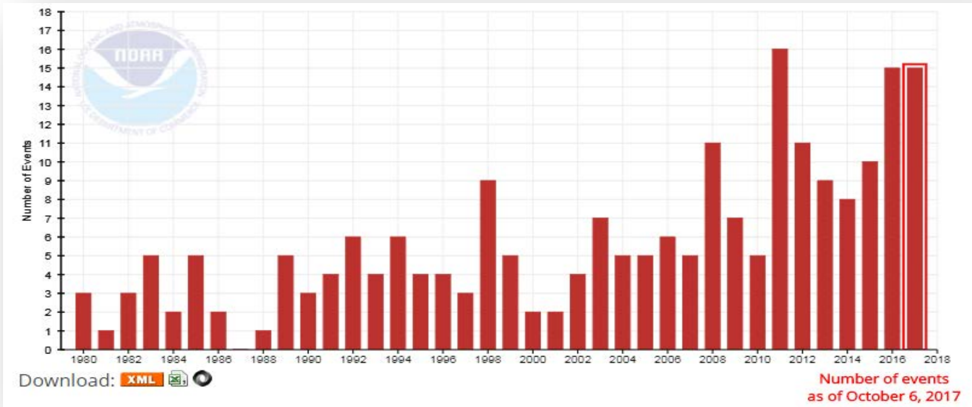


Figure 1 - Billion dollar disaster type events (NCEI, 2017)

The current water enterprise is a sophisticated and expansive capability that has developed over decades. NWS plays a key role in the enterprise. In its capacity, NWS maintains 13 regional River Forecast Centers (RFCs), which are the front-line NWS river forecasting entities. These 13 RFCs (whose regions are shown in Figure 2) ingest a variety of water data sources to develop near, medium, and longer term river forecasting results. For instance, primary data sources are the U.S. Geological Survey (USGS) stream gauge information. These gauge locations (see Figure 3), are dispersed throughout the continental United States and represent the locations where forecasts are generated by the RFCs. NWS also maintains 122 Weather Forecast Offices (WFOs) that issue flood warnings. More recently, NWS stood up the National Water Center (NWC) and the National Water Model (NWM), with a goal of advancing the state of the art in terms of forecasting, in this case vastly expanding the number of forecasting points from 3600 using a lumped model approach to roughly 2.7 million points, using a distributed model approach (see Figure 3). Another key component is NWS Weather Prediction Center, and the resultant rainfall forecasts that are forcings used within the RFC models. A variety of other sources are used as well, to include other national-level data sources such as U.S. Department of Agriculture (USDA) Snow Telemetry (SNOTEL) data or regionally or locally-provisioned data such as state or locality stream gauge information. Each of the RFCs integrates these regional and local data sources to help enhance their river forecasts. As these data and forecasts are collected and produced, they are made freely available via NWS websites and web services.

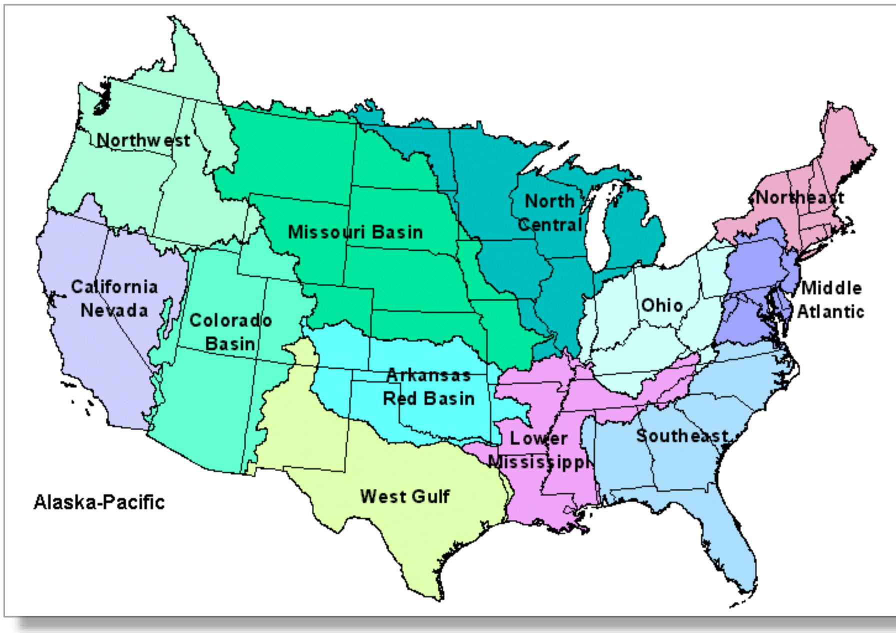


Figure 2 - National Weather Service River Forecast Center Regions (NWS, 2017b)

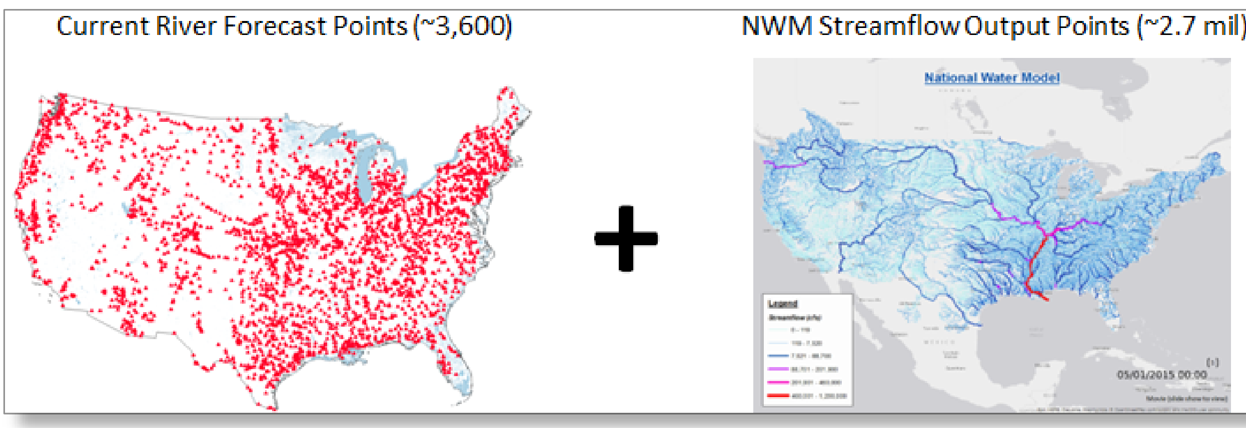


Figure 3 - RFC (left panel) and National Water Model (NWM) (right panel) forecast points (NWS, 2016)

As these forecasts are made available, the RFCs then work closely with their core partners to help integrate the results into their operations. These partners are wide ranging, from the U.S. Bureau of Reclamation (USBoR) and U.S. Army Corp of Engineers (USACE) with their dam management operations, to the Federal Emergency Management Agency (FEMA) and local emergency responders engaged in managing responses to flooding, and to water utilities seeking to ensure safe and reliable supplies of water to their customers, to the general public, and to many more users of the information.

The RFCs also support water resource managers with risk-based, decision support for a variety of water resources applications, including reservoir operation, flood forecasting, river navigation, and water supply. The current operational probabilistic forecasts are limited in that they only address long-range meteorological uncertainty (via climatologically-based ensemble forcings) and do not account for hydrologic model, parameter, and initial condition uncertainty. To address the limitations of existing operational hydrologic forecasting and to meet these stakeholder needs, NWS has developed, tested, and is currently implementing the Hydrologic Ensemble Forecasting Service (HEFS). HEFS explicitly accounts for all aspects of uncertainty inherent in both the meteorological and hydrologic forecasts. HEFS has been deployed operationally at all thirteen of NWS RFCs, and as of 2018, the RFCs are running the HEFS every day in real-time and providing forecast products at 855 locations across the country.

In addition to the river forecasting provided by the RFCs, NWS National Hurricane Center (NHC) also provides storm surge forecasting due to hurricanes. The Storm Surge Unit at the NHC uses the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model to perform this forecasting, which incorporates pressure, temperature, forward speed, and track data from tropical cyclones, in addition to a variety of topographic elements to perform this modeling (NHC, 2017).

1.1 Water Enterprise Complexity

The water enterprise is significantly more complex than described above. As compared to the weather enterprise, where there are fewer, larger participants, the water enterprise is significantly more diverse and diffuse. For instance, while the RFCs provide river forecasting at approximately 3,600 locations, those only represent a small portion of the possible, required forecast locations. Currently these other locations may or may not have forecasts, and if they do, some other entity is performing the forecasting, perhaps a local flood control district, a private company, a university, or a non-governmental organization. They are likely using different tools, different datasets, and delivering different types of results.

Other complications arise when multiple entities provide water forecasts in the same region for different missions. For example, perhaps it might include an RFC, the USGS, a private forecasting firm, and the Federal Emergency Management Agency (FEMA), as happened recently during Hurricane Harvey in Texas. This can prove challenging for a state emergency operations center that is under pressure and has limited resources to integrate forecasting results coming from multiple entities.

Further complications exist in the form of the significant anthropogenic operational rules involved with managing water resources. A number of federal, state, and private entities are involved with managing dams and reservoirs; whether for flood control, hydroelectric power generation, or irrigation; and they operate rather independently with different sets of operational rules. A hydroelectric power generation dam might be looking to optimize power generation and so has a particular set of rules to meet those requirements; whereas a flood control dam is more interested in preventing flooding inundation and so operates with a different set of operational rules. Very often the dams are multipurpose, with complex sets of rules that seek to balance the competing interests. These human decisions for releasing water have significant impacts on downstream water conditions so it is optimal to closely integrate them into NWS and other forecasting models. This requires significant coordination across a variety of entities. Recognizing these complexities, the water industry is advancing creative innovations to help.

2. STUDY METHOD

2.1 Research Questions

To help NWS understand the state of change and complexity of the water industry, we posed the following core research questions:

- What is the current state of the art for water forecasting in the private industry?
- What are the near to medium term technological and policy innovations occurring in the private industry?
- How does the private industry view the role of NWS in the water enterprise today and in the future?

2.2 Approach

To answer these questions, we used the following techniques:

- **Literature Review** - We conducted a standard literature review. It should be noted that with this review there was a heavier emphasis on reports emanating from recent water symposia and conferences rather than from journals.

- **News Articles, Company Press Releases, & Websites Review** - News articles and company press releases and websites were also reviewed to help identify company main water-focused products and services as well as recent or emerging indications of enhancements.

- **Private Industry Interviews** - We performed telephone interviews with a cross section of private companies working in the water enterprise.

- **Government Expert Interviews -** We interviewed a number of leading government experts in the water enterprise to understand their current capabilities, perspectives, challenges, and innovations.

2.3 Water Enterprise Components

When discussing the water enterprise, NWS has roles and responsibilities that center around water quantity forecasting. There are three primary components to meet these roles and responsibilities. While there are other water-related tasks within the greater water enterprise, they are not considered as part of this effort, only those roles for which NWS has responsibility. These components include:

1. **Monitoring & Observation -** The first component involves collecting the data that is then subsequently used in forecast modeling. A variety of data sources and data providers are used as part of the water enterprise. Many of these data sources are provided by external partners. Some of the larger, more important ones include stream and rainfall gauges, rainfall forecasts, snowpack levels, water resources operational rules (dams/reservoirs), tidal gauges, river dimensional model, digital elevation, hurricane forecasts, oceanic, bathymetric and topographic data, and model features. These are provided by a number of partner organizations that include National Ocean Service (NOS), United States Geological Survey (USGS), United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), United States Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), Environmental Protection Agency (EPA), Bureau of Reclamation, Bureau of Land Management, US Forest Service, State Departments of Natural Resources, Local/County flood control districts, and hydropower operators. These data are often augmented with other regional/local sources that are then integrated into the RFC's modeling.

2. **Modeling & Forecasting -** Once data has been collected and quality controlled, it is then integrated within different forecasting models. A number of different models are used focusing on different components of the forecasting. For example, the Weather Prediction Center (WPC) provides precipitation/rainfall forecasts which are then fed into RFC river level forecasts. Similarly, the National Hurricane Center (NHC) Storm Surge Team performs storm surge modeling using hurricane forecasts coming from the NHC. The NOS also creates storm surge models and output. There are many instances where other groups perform their own modeling, including USACE and the USBoR and their dam operations modeling, or local flood control districts that incorporate

high quality, very localized data to support urban-scale flood modeling. It is useful to note that the models tend to focus on the water extremes: forecasting flooding and droughts, with significant more historical emphasis having been placed on the flooding problem. It is also useful to note that the RFCs currently use a lumped model approach where basins are considered homogeneous whole spatial units, whereas the National Water Center (NWC) has recently deployed the NWM which provides a continental-wide distributed model with approximately 2.7 million forecasting points.

3. **Service Delivery** - From NWS perspective, the third component is its delivery of products and services to stakeholders and the public. There are two primary components to the service delivery: decision support and communications. Decision support centers around helping to integrate the outputs from NWS forecast models into the workflows and systems of their partners. So for instance, outputs from NWS Hydrologic Ensemble Forecasting System (HEFS) were integrated into the New York City Department of Environmental Protection Decision Support Tool, allowing New York City to save billions of dollars in potential infrastructure investments. The communications component deals with how the product or service is delivered to the partner. This often comes in the form of a static image, mapping layers, or alerts or also via web services that support machine-to-machine communications.

An additional, broader component considered in this report is referred to as the **Business of Water**. This component deals with how the water enterprise community works together to advance the state of the art of the enterprise. It is where the roles and responsibilities between NWS and other federal entities are defined versus those of the private industry. It involves the collaborative process of defining water data exchange standards. As will be discussed below in the Water Enterprise Context section, a number of recent initiatives have sought to address some of these concerns.

2.4 Scope

Given the diversity and expansive nature of the water enterprise, we restricted the scope of this report and established the following scoping constraints:

- **Private Industry Focus** - While we recognize that a great deal of innovation also occurs in the academic and governmental organization spaces, we primarily focused our attention on innovation stemming from the private water industry. We only deviated from this constraint when we felt there was a high visibility contributor whose input would be very valuable to the report.

- **U.S. Focus -** We also recognize that there is significant hydrological expertise internationally. Again, due to the time constraints of this project, we focused our research and interviews on primarily U.S. based efforts. We did interview a few international companies, or at least the U.S. branch of an international company, when we believed that they were either a major contributor in the water enterprise or they had a very unique, innovative offering.

- **Established Entities with Relative Technological Maturity -** We also restricted our interviews to focus more on either established companies that have a history of interesting hydrologic technologies, or newer companies that have technologically mature products and services. There were a number of initiatives that were not at a sufficient technological maturity to warrant further investigation for this report.

3. RECENT AND RELEVANT ACTIVITIES

There have been a number of recent activities aimed at advancing the state of the water enterprise. Some of these larger efforts are outlined here to provide background and context for the current water enterprise.

3.1 2013-2017 Water Resource Services Branch Stakeholder Engagement

NWS Water Resource Service Branch engaged its key stakeholders for many years to better understand how to deliver more relevant products and services to these users (NWC, 2017c). These engagements took take place under the auspices of an Integrated Water Resources Science and Service multi-agency federal initiative from 2012 to 2016. In 2017, the Water Resource Services Branch (WRSB) continued stakeholder engagement by holding regional forums that included focused sessions on inundation, uncertainty, and departure from normal streamflow. These have been used to help inform NWS hydrologic operations in general and future planning.

3.2 2014 Federal Geographic Data Committee (FGDC) and Advisory Committee on Water Information (ACWI) Open Water Data Initiative

In 2014, the FGDC and the ACWI under the Subcommittee on Spatial Water Data launched the Open Water Data Initiative (FGDC, 2014). The goal of this initiative includes:

> "The goal of the OWDI is to integrate currently fragmented water information into a connected, national water data framework by leveraging existing systems, infrastructure and tools to underpin innovation, modeling, data sharing, and solution development. Moreover, the adoption of community data standards, protocols, and ontologies is critical to this effort."

This initiative laid out a roadmap called the Open Water Web that includes a Water Data Catalog, Water Data as a Service, Enriching Water Data, and Community for Water Data/Tools. These were then further examined and prototyped via three use cases to include (i) National Flood Interoperability Experiment (NFIE), (ii) Drought Decision Support Tool, and (iii) Spill Response Tool. NFIE, in turn, helped NWS accelerate operationalizing the NWM as a result.

3.3 2015-2017 Aspen-Nicholas Water Forum

The Aspen Institute and the Nicholas Institute (Aspen-Nicholas, n.d.) have been holding an annual Water Forum to address domestic water challenges in the 21st century. The 2015 forum on *Data Intelligence for 21st Century Water Management* is particularly relevant as it focused heavily on water data. The report identified five key findings as follows:

1. The rise of big data and new measurement technologies can transform the way that water is managed in the coming decades.
2. However, water data must be synthesized more rapidly than government agencies' current pace of analysis.
3. A national water data policy is needed that standardizes data integration and storage for more effective water management across sectors.
4. Overcoming privacy constraints would help to maximize the potential of water data.
5. Accurate assessments of private industry water risk require better matched data sources and data analytics across industry.

3.4 2016 NWS Regional Water Conversations

NWS held a series of regional water conversations to engage key stakeholders on NWS water services (Graziano, 2016). The conversations validated that River Forecast Centers (RFCs) are highly valued and confirmed that for water resource users, IDSS includes both event-driven, high-impact events and routine, high value decision making. Key requests from these conversations include:

- Account for anthropogenic processes across all prediction platforms;

- Verify and validate;
- Provide uncertainty information for forecast guidance on all time scales;
- Extend the forecast range of the National Water Model (NWM);
- Provide more high performance computing capacity for the NWM;
- Continue the implementation of the Hydrologic Ensemble Forecast Service (HEFS);
- Sustain engagement (End-to-end leveraging social science best practices);
- Improve quantitative precipitation forecasts on all time scales; and,
- More stream gages.

3.5 2016 NOAA Water Initiative

NOAA kicked off a Water Initiative in 2016 which "calls for a boundary-spanning partnership across multiple sectors to create and deliver water information to meet the needs of the 21st century" (NOAA, 2016). This initiative identifies five objectives:

1. Build strategic partnerships for water information services.
2. Strengthen water decision support tools and networks.
3. Revolutionize water modeling, forecasting, and precipitation prediction.
4. Accelerate water information research and development (R&D).
5. Enhance and sustain water-related observations.

Within each of the objectives, a number of outcomes are identified as well with specific yearly timeframes for achieving the objectives.

3.6 2017 Aspen Institute Dialogue Series on Water Data & Internet of Water Report

In addition to the Aspen-Nicholas Water Forum, the Aspen Institute also recently held a Dialogue Series on Water Data which produced a report called *The Internet of Water* (Patterson et al, 2017). This report calls out a number of fundamental questions that we cannot readily answer concerning water:

- How much water is there?
- What is its quality?
- How is it used?

The report identifies the following key findings:

1. The value of open, shared, and integrated water data has not been widely quantified, documented, or communicated.
2. Making existing public water data open is a priority.

3. The appropriate architecture for an "Internet of Water" is a federation of data, producers, hubs, and users.

Finally, the report identifies a number of recommendations (only the top level actions are shown here):

1. Articulate a vision.
2. Enable Open Water Data.
3. Create an Internet of Water.

Each of these is further delineated into more specific recommendations and may be found in the report.

3.7 2017 National Weather Service (NWS) Weather Enterprise Analysis Report

In 2017, NWS Office of Organizational Excellence embarked on the task of completing a Weather Enterprise Analysis report (NWS, 2017a). This effort sought to understand innovations occurring in the weather enterprise that could impact NWS operations, and to help NWS better position itself to collaborate with the private industry on these innovations. Given NWS's role in forecasting weather, water, and climate, this 2017 weather report was the precursor to this current water industry analysis report. This current water report is the second of three likely reports focusing on private industry innovations in the given enterprise. Given the significant overlap between the weather and water enterprises, many of the innovations and industry directions identified in the weather report are applicable to this report as well.

4. FINDINGS AND RECOMMENDATIONS

Innovations are identified according to their water enterprise component and are called out as **findings** below. We heard **recommendations** from a variety of people about how they would like to see the water enterprise take shape over the coming years. They are noted accordingly.

4.1 Monitoring & Observation

Findings:

1. *The spatial-temporal resolution of observations and supporting data is increasing significantly.*

A universal theme we heard was that the spatial-temporal resolution of observations and supporting data layers was increasing significantly. We see a number of companies engaged in or leveraging the results of high-resolution data collection initiatives, especially over large urban environments. For instance, companies reported that 10m spatial resolution elevation data was still not high enough to adequately support urban flood modeling and that cities and regions were funding higher resolution LiDAR data collection efforts to meet these requirements.

2. *The Internet of Things (IoT) will proliferate more sensors and new types of sensors, which have the potential to unlock many new data streams.*

IoT has the potential to dramatically expand the number and types of sensors in support of hydrologic modeling. To date, however, these have mainly been limited to pilot projects. Big changes leading to the IoT revolution and adoption include reduced hardware/sensing costs, the deployment of IoT-specific networks (Ingenu, 2017; GSMA, 2017; Lora Alliance, 2017), and the emergence of simplified data interoperability standards (Liang et al, 2017). Quality Assurance / Quality Control becomes a bigger issue as the sensors are not considered professional grade yet for hydrologic modeling, but with the addition of a large number of sensors, some of these concerns might be overcome as the results coming from the multitude of sensors could be used to cross check each other.

In addition to the increase in the sheer number of sensors, there is also an increase in the measurement type that these sensors are taking. For instance, USGS is not only measuring stream levels and flows, but also measuring stream temperatures, dissolved oxygen levels, turbidity, and environmental DNA (eDNA) which are all elements of determining water quality.

Finally, there are a number of notable sensor deployments worth mentioning. Bridge-based, river-level air gap sensors are becoming more common. These can be ultrasonic sensors that are positioned on the side or bottom of a bridge, allowing one to measure the height of the river. Another interesting effort involves the use of drones during flash floods which are used by both the private and public sectors. Hodson (2013) reports that Saudi Arabia has been investigating the use of drones to provide flash flooding warning by deploying a series of sensors with real-time communications.

3. *Crowdsourcing of social network-derived data shows potential to augment traditional hydrologic sensing sources.*

During the 2017 hurricane season, we saw instances of groups leveraging social media to share real-time flooding inundation information. The MIT RiskMap (MIT News, 2017) was used by Broward County, FL during Hurricane Irma, to help report information about flooding inundation. Figure 4 shows an overview of the types of information collected via the RiskMap program. While any individual flood depth coming from these reports may not be accurate, by crowdsourcing this information via potentially large numbers of such points, one could leverage this information to develop a flooding inundation map.

Figure 4 - RiskMap.us video demonstrating how it allows users to crowdsource flooding information to include location, flood depth, photos, and a textual description (MIT UrbanRISK Lab, 2017)

4. *Groundwater and soil moisture data are significantly underrepresented.*

Groundwater and soil moisture information continues to be significantly underrepresented in terms of observations. As opposed to rivers where the USGS has established a significant number of stream gauges, such a robust sensing network is missing for groundwater and soil moisture, both critical components for hydrologic modeling. The USDA NRCS maintains the Soil Climate Analysis Network (SCAN) that provides soil moisture at over 200 stations; however this covers a small fraction of the number of NWS-forecasted sites. USGS has researched techniques for measuring soil moisture using remote sensing (USGS, 2016) and the recent launch of the NASA Soil Moisture Active Passive (SMAP) mission (NASA, 2017) now allows for continuous soil moisture monitoring down to 5 cm with a grid size of 10 km. While an improvement, this still does not provide refined enough measurements to support flood modeling at the urban scale.

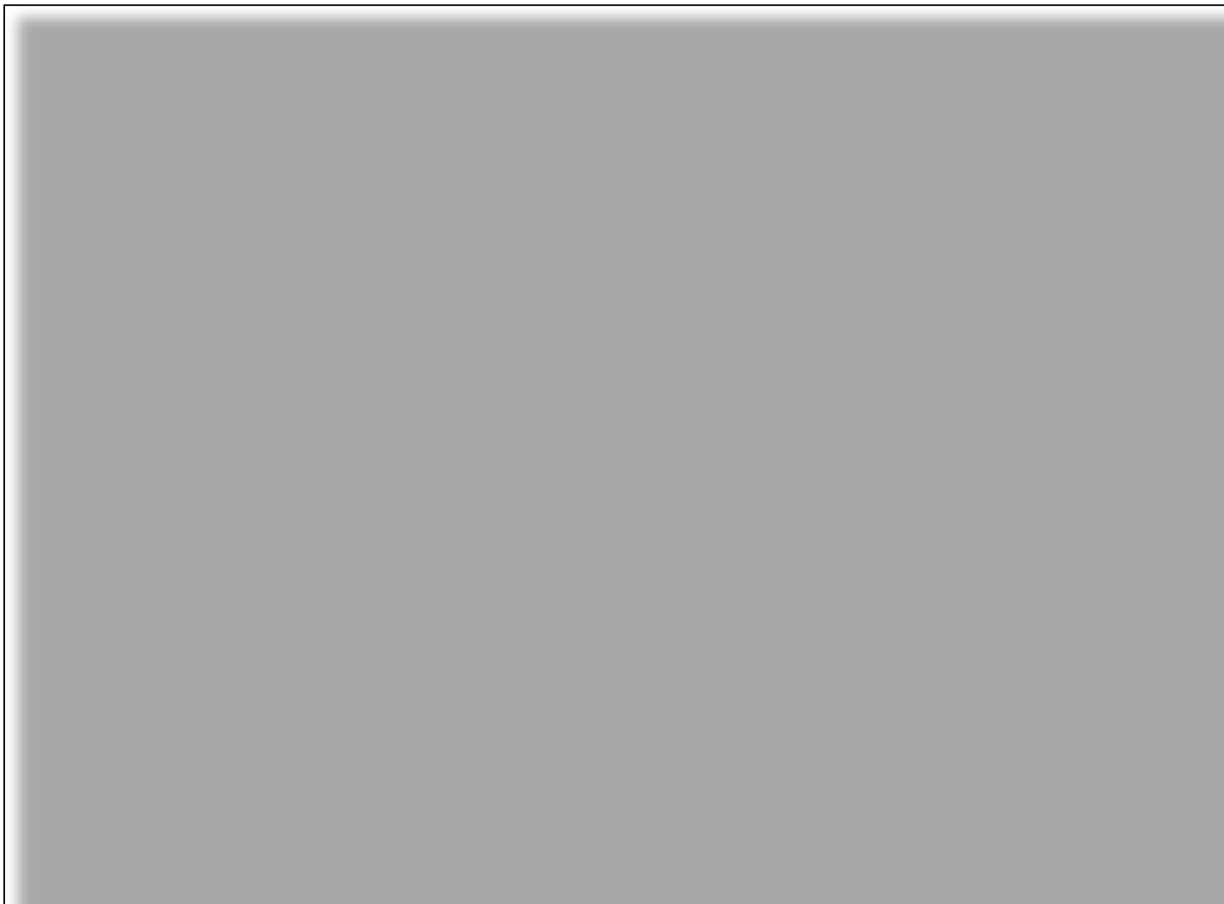


Figure 5 - Soil Moisture map collected by the NASA SMAP mission (Morisette, 2015)

Recommendations:

1. *Data access needs to be improved as current limitations due to proprietary and closed systems continues to prove challenging.*

Another common thread heard from many companies was related to the challenges associated with proprietary data access. This often arose in the context of gaining access to hydropower or other operational rules with regards to expected water releases. Currently much of this information is considered business proprietary, causing those hydropower companies to only release the data to a limited number of organizations, who can use the data in their modeling, but must not release the raw data. This puts the private industry at a significant disadvantage when it comes to understanding the entire water budget for a region. This raises the question of when can water data be considered confidential and when must it be publicly available?

4.2 Modeling & Forecasting

Findings:

1. *Hyper-localized modeling is a significant focus for many companies.*

Many companies are investing heavily in hyper-localized flood modeling, especially for large urban areas. Given the 2017 hurricane season and the significant damage inflicted on the Gulf Coast states, many companies are now seeing a return on investment for this type of modeling. These companies are combining highly detailed models of the sewers with high resolution LiDAR-derived elevation models with detailed river/stream models and more. Combining surface water and groundwater was a common theme. The goal is to completely account for all of the water in and around an urban environment. The model outputs can provide more precise spatio-temporal flooding results, but at a computational and data input/management cost. With all of this hyper-localized modeling and the fact that the RFCs operate independently, this leads to a very distributed water enterprise where each river basin is often handled differently.

There is significant interest in exploring how best to integrate this hyper-localized modeling into the NWM. For instance, some companies mentioned performing modeling at the 10m or higher resolution scales whereas the NWM operates at the 1km and 250m scales. A major goal is to take the forcings from the NWM and use those to help drive these hyper-localized models.

Similarly, the results of these hyper-localized models could be used as feedback to inform the NWM. Many companies have already or are thinking about testing the NWM and they recognize that it will need to be modified and tuned before it becomes fully operational. A robust mechanism for providing feedback to the NWM from these explorations and hyper-localized model results should be enabled.

2. *Multi-domain modeling is becoming more routine.*

The coupling of hydrological modeling outputs to other modeling systems is becoming more common and in demand. For instance, multiple companies mentioned that, in addition to basic hydrologic modeling, they are modeling sediment runoff to understand the growth of harmful algal blooms. Other companies were also modeling water quality to understand the impacts to public health.

A number of companies are also working to integrate policy and legal content into their hydrologic models. For instance, some companies are attempting to integrate water rights with their models as a means towards understanding the demands placed on a river and the need for future water supplies.

3. *Newer water quantity prediction modeling capabilities are being built and deployed in the cloud as separate services with distributed, scalable analytic engines.*

Following the approach of many of the leading private, high technology companies, a number of the water companies have split apart their modeling capabilities into separate services that can be called independently. Amazon was one of the first high tech companies to push this service-level approach back in 2002. Scalable analytic processing is a critical component of this hydrologic modeling, providing the ability to ramp up or down the number of processing nodes or cores to perform the forecast modeling. NWS found that the primary technology companies with whom we spoke were the leaders in providing these service-based capabilities. A number of the traditional hydrologic modeling companies are only beginning to consider migration to a cloud platform and separating out their software into discretized services.

4. *Companies are working to assimilate new sensor data with their models.*

As noted by Houser et al (2012), data assimilation is the process of combining hydrologic models with observations to provide improved hydrologic state estimates. Data assimilation is a high priority for many companies as they seek to improve their model outputs with the various new hydrologic sensors. A number of challenges exist to successfully accomplish this data assimilation. For instance, how and where does one characterize the error?

5. *Incorporating water quality data into forecast modeling is becoming increasingly important.*

Many companies are beginning to incorporate water quality information into their hydrologic modeling. On the federal agency side, there are strong collaborations already happening through the Water Quality Data collaboration between the USGS, EPA, and the National Water Quality Monitoring Council (NWQMC) (NWQMC, n.d.) and the recently released EPA Hydrologic and Water Quality System (HAWQS) (EPA, 2017).

6. *Machine Learning has the potential to dramatically impact forecast modeling but to date it has not been widely deployed.*

Machine Learning is gaining adoption in a number of industries such as transportation, healthcare, finance, humanitarian aid, and space exploration (Eastwood, 2017), and advanced techniques such as Deep Learning have demonstrated better-than-human performance in a number of tasks (Yao, 2017). However adoption in the hydrologic modeling space is limited. With increased hydrologic data collection and the application of techniques such as Deep Learning (Kiser, 2016), research into the application of machine learning to hydrologic modeling may yield advances.

7. *Significant demand exists for longer range, climate-adjusted forecasting.*

Many companies indicated a desire to use three month, six month, yearly, or even multi-year forecasts that reflect climate variabilities. Water utilities companies who perform multi-year, long-range planning for new infrastructure were particularly interested in these longer-range forecasts.

8. *The use of open source water quantity prediction software and frameworks is growing.*

A number of companies are leveraging and contributing to open source hydrology software packages or frameworks. For instance, the WRF-Hydro package hosted by UCAR (UCAR, 2017) and the Deltares FEWS software (Deltares, n.d.) are two open source software packages that are leveraged by a number of companies. This trend might be an opportunity for NOAA to leverage for its own operations.

Recommendations:

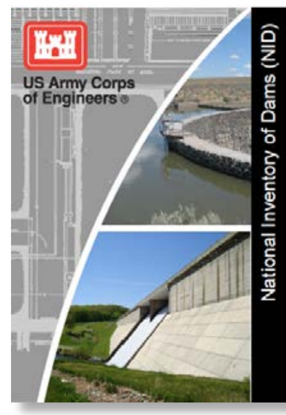
1. *Support multi-model ensemble river forecasting in each basin.*

Currently the RFCs provide river forecasting for their respective regions and in many cases, they might be the only entity providing forecasting for the various river basins. With the introduction of the NWM, now there will at least two river forecasts provided for the RFC-covered river basins. We heard from companies recommending that NWS should support this sort of multi-model ensemble river forecasting and not attempt to only have a single forecast for a river basin. The rationale was for this recommendation was that ensemble forecasting will lead to a better a characterization of the uncertainty of the models.

2. *NWS should be responsible for the large-scale data processing and then provision those results to the private industry for value-added capabilities.*

We heard from a number of vendors that they would like for NWS to be responsible for the large-scale modeling that requires extensive computing time and on-site expertise, and to then provide the results of those model runs to the private sector for subsequent value-added products and services.

3. *Dams, reservoirs, and diversion data and operations should be incorporated into the NWM and a national inventory of dams, reservoirs, canals, levees, and water-related infrastructure should be created.*



The USACE maintains a National Inventory of Dams that, starting in 2017, is updated annually (USACE, 2016). The USACE also maintains a companion National Levee Database that includes an inventory of most of the USACE levees; however it is not comprehensive of all levees in the U.S. A number of companies recommended that these inventories be expanded to be more comprehensive of all water infrastructures to enable incorporation into water models. The companies also recommended that the anthropogenic water operations associated with this infrastructure be incorporated into the NWM for a more complete accounting of the national water budget. Finally there was general interest in developing a more standardized data structure or methodology for incorporating these anthropogenic operations into water models.

4.3 Service Delivery

Findings:

1. *Customized heavy-client solutions are starting to give way to more cloud-based services solutions, although adoption is slow.*

While many of the water modeling companies are still primarily focused on providing heavy-client desktop modeling solutions, a significant number of them have already or are in the progressing of migrating their software to work in the cloud. The companies that started as technology companies and then grew expertise in the hydrologic modeling space tend to be the leaders in cloud implementation. Some of the leading, larger pure hydrology companies have also transitioned and now provision commercially available services.

2. *Robust access to quality-controlled data via user-friendly web services and applications with the ability to quickly filter to return data of interest is a key user requirement.*

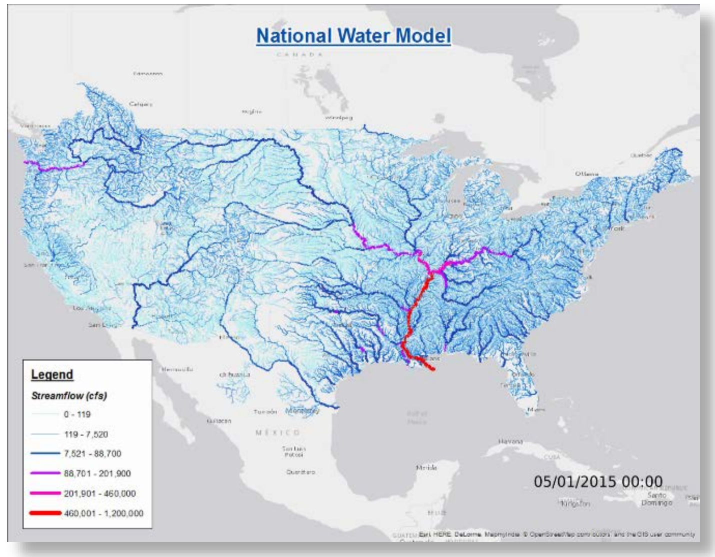
The majority of the companies rely heavily upon NWS data and forecasts to incorporate into their own models and value-added capabilities. As part of this workflow, many companies highlighted the requirement for robust access to NWS quality controlled hydrology data and forecasts via flexible web services. These services should provide robust spatial, temporal, and attribute filtering and output format specification to enable a customer to be able to automatically retrieve notification of and data of the NWM short-range forecast over a given river basin in a user-friendly format for example. We heard the theme "data portfolio definition", or defining the types and specifications of data required to run a given hydrology model. This data portfolio definition could provide a just-in-time data supply chain that, if provisioned correctly, would prevent downstream users from having to create their own data warehouse of hydrologic content. Providing a robust web capability for such data portfolio definitions would go a long way towards meeting the requirements of many companies.

Another theme we heard was that there are too many webpages, many of which are difficult to use, when one wants to access NWS water data. Providing more standardized access with a robust query capability across NWS water enterprise would help alleviate this challenge.

3. *Companies are exploring novel methods for visualizing larger volume, higher dimension, higher resolution data that are user appropriate.*

We heard from many companies that they are pushing the bounds of advanced visualization techniques for viewing and interacting with the model outputs. They are moving into the visual analytics realm where a given visualization has a wealth of underlying content that can be rapidly accessed, to include visualizing the errors propagated throughout the forecasting models. Focus is not only on advanced visualization software and algorithms, but also on novel hardware as well to be able to handle the higher resolution, more dynamic data content.

4. *Many companies rely upon NWS approved forecasts for liability reasons.*



A number of companies mentioned that if they are going to use a water model to make major decisions, they want to be sure that it is a nationally recognized and validated model. For instance, a water utility needing to make a 25-year infrastructure investment decision requires a robust and validated long-range model that they can use to help inform their decision making. In fact, some of the companies indicated that they would forego more advanced, yet unvalidated, capabilities from third parties in favor of a less advanced, but validated, NWS model output.

This raises a number of questions regarding model validation. What does it mean to validate a hydrology model, who oversees andapproves the validation, and what is the process for obtaining this validation? Could a non-federal governmental entity perform this validation on behalf of the government? These questions will need to be addressed to help further the adoption of more advanced private industry capabilities that may require some sort of government seal of approval.

5. *Water data interoperability standards exist but it is unclear how widely adopted they are currently.*

The current Open Geospatial Consortium (OGC) standard, WaterML 2.0, is a useful capability that provides a common semantic model for water data interoperability in an Extensible Markup Language (XML) format (OGC, 2017). It includes four parts that cover:

1. Timeseries;
2. Ratings, Gaugings, and Sections;
3. Surface Hydrology Features; and,
4. GroundWaterML.

WaterML 2.0, Part 1 - Timeseries, served as one of the motivations for the OGC TimeseriesML standard as well, that has since been adopted by the World Meteorological Organization (WMO). These standards provide XML standards; however they should be further enhanced to include a JavaScript Notation (JSON) data format variant, which is a popular web service data exchange format that would help with user adoption.

Another notable and relevant OGC standard is the IoT SensorThings API (Liang et al, 2016). This provides a means for communicating observational information within an IoT framework and can be applied to the hydrology domain.

6. *Expect closer coupling of hydrologic model outputs to customer capabilities.*

We saw a number of highly integrated capabilities by companies where publicly available NWS forecast results were tightly integrated into customer products and services, and we expect this trend to continue. A good example comes from a prominent water utility, looking at revenue forecasting through water and rainfall forecasting. This company seeks to understand the relationship between customer water usage patterns and weather and hydrology patterns and being able to project that forward in time. NWS forecasts provide that company a better understanding of their projected revenue stream.

7. *Near-Real-Time, Mobile Reporting is Trending.*

Near-real-time, mobile reporting of hydrologic model outputs is currently very popular, especially given all of the recent hurricanes and associated flooding. Many companies provide mobile application-based capabilities for delivering their forecasting results. One company, for instance, is looking to couple a Google Map StreetView capability with their flooding forecasts to enable a user to be able to look up his or her house and see what the projected flooding would look like.

Recommendations:

1. *NWM should provide two sets of outputs: one that includes anthropogenic factors such as dam operations and one that does not.*

As companies are seeking to integrate the NWM outputs into their own systems, they requested that two flavors of output be made available: one that only includes unregulated, natural water flows and one that includes regulated flows via anthropogenic decisions such as dam operations. They raised the concern that if only partial anthropogenic operations are included that it makes it less useful as it will be inaccurate but one will not necessarily know where it is inaccurate.

2. *Allow interactions between the private industry and NWS during water events to enable them to better understand the shape and temporal dynamics of the storm.*

Some companies mentioned the desire to be able to meet face to face with NWS personnel to discuss the shape and temporal dynamics of a storm during the event. As they are often involved with the hyper-localized modeling mentioned above, they have a goal of helping the cities mobilize resources to help respond to major water events. As part of this, NWS should provide a mechanism by which these private companies can provide feedback to the NWM from their hyper-localized modeling.

3. *Synthesize water modeling and forecasting across all of the federal agencies before delivering to state or regional emergency responders.*

Recent events during Hurricane Harvey demonstrate the desire to have a more unified federal front when it comes to flood forecasting. Some companies believe that this synthesis should be occurring at the NWC and should require integrating results coming from multiple agencies such as EPA, FEMA, USDA, USACE, and more. Without doing this, the state, regional, and local emergency responders are left with trying to integrate results from multiple agencies in real-time under stressful situations.

4.4 Business of Water

Findings:

1. *The uncertainty of future NWS hydrologic services and direction is causing private industry to pause investments.*

A fair amount of uncertainty exists within the private water industry when it comes to the expected hydrology services and direction of NWS. Companies indicated that they are not investing in certain efforts as it is unclear NWS will soon be providing a similar, competing service that would cause them undue financial hardship. Questions that arise based on this finding include:

- Where do the hydrologic roles and responsibilities of NWS start and stop and where do those of the private industry pickup?
- Are there inherently governmental functions that should be kept with NWS and if so, what are they?
- Where can technological innovation be best handled by the private sector?

Recommendations:

1. *Find a mechanism by which NWS can engage with private, nonprofit, and academic entities without fear of bias towards a particular partner.*

We asked all of the companies how they would like to collaborate further with NWS. All of them were very interested in more collaboration, but many noted that in their previous attempts to engage with NWS, often NWS personnel were hesitant to engage for fear of demonstrating a bias towards that company. The question that arises then is how a level playing field can be established that enables technological innovation and a free-flowing dialogue between NWS and its private industry partners? The right form, structure, and environment needs to be defined to bring together private, nonprofit, academic, and government experts to advance the state-of-the-art with respect to the water enterprise. The Aspen Institute's *Internet of Water* report states:

> "The Internet of Water follows the organizational structure of the Internet with a backbone organization that provides support and governance structures to ongoing data sharing communities; connecting these communities to one another." (Patterson et al, 2017)

This Internet-based model could be considered when determining how best to enable the advancement of the water enterprise.

2. *Develop mappings of key water players and their capabilities, roles, responsibilities, and funding for a given region to better understand the water enterprise.*

Given the significant complexity between water partners in the regions, a recommendation was made to start mapping out the capabilities, roles, and responsibilities for the water enterprise in the different regions. This would include, for instance, a delineation of the hydrology modeling roles and responsibilities, similarities, and differences between the RFCs, the USACE, the USBoR, and more. By examining these factors, one can start to understand the inner workings of the Enterprise. If solutions to improve the Enterprise are desired, then one needs to understand all components of the Enterprise, for otherwise optimizing one component might inadvertently degrade another.

5. SUMMARY

With many significant, large trends underway, NWS will need to take a strategic perspective with respect to our roles and responsibilities within the larger water enterprise. The findings and recommendations identified in this report will act as input to a larger discussion for how the NWS moves forward to enhance the water enterprise and to establish lasting partnerships with the private water industry.

Some specific recommendations that NWS will explore going forward include:

- Engaging with the water enterprise through consistent activities and interactions;
- Continuing to define NWS's role in the water enterprise to enable the water industry to grow and innovate;
- Harnessing external capabilities to take advantage of advances throughout the water enterprise; and,
- Communicating NWS's strategy and unique role as an enabler of the water enterprise.

APPENDIX 1 - ACRONYMS

BLM	Bureau of Land Management
eDNA	Environmental DNA
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
GPGPU	General Purpose Graphics Processing Unit
HAWQS	Hydrologic and Water Quality System
HEFS	Hydrologic Ensemble Forecast Service
JSON	JavaScript Notation
LiDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NFIE	National Flood Interoperability Experiment
NHC	National Hurricane Center
NOS	National Ocean Service
NRCS	Natural Resources Conservation Service
NWC	National Water Center
NWQMC	National Water Quality Monitoring Council
NWS	National Weather Service
NWM	National Water Model
OGC	Open Geospatial Consortium
OWP	Office of Water Prediction
RFC	River Forecast Center
SCAN	Soil Climate Analysis Network
SLOSH	Sea, Lake, and Overland Surge from Hurricanes
SMAP	Soil Moisture Active Passive
UCAR	University Corporation for Atmospheric Research
USACE	U.S. Army Corps of Engineers
USBoR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WFO	Weather Forecast Office
WMO	World Meteorological Organization
XML	Extensible Markup Language

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