Opportunities for Forecast-Informed Water Resources Management

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The American Meteorological Society (AMS) is a scientific and professional society of roughly 13,000 members from the United States and over 100 foreign countries.

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About the AMS Policy Program

The AMS Policy Program has two primary goals. The first is ensuring that policy choices take full advantage of information and services relating to weather, water, and climate. The second is making sure that policy makers understand how much the broader society's welfare depends on information and services relating to weather, water, and climate. Meeting these two goals will help ensure that the scientific community receives the support and resources it needs to be able to make critical information and services available and, most importantly, will help the nation, and the world, avoid risks and realize opportunities related to the Earth system.

The Policy Program uses three primary approaches to help meet these two goals.

- We develop capacity within the AMS community for effective and constructive engagement with the broader society.
- We inform policy makers directly on established scientific understanding and the latest policy-relevant research.
- We help expand the knowledge base needed for incorporating scientific understanding into the policy process through research and analysis.

Through these activities, we create new ways to reduce society's vulnerability to weather and climate events by sharing our resources and information with policy makers and the public.

Executive Summary

Greater use of weather and hydrologic forecasts can help us manage our nation's water resources more effectively and minimize the risk of future extreme floods and droughts. Although forecasts have become more skilled at temporal and spatial scales relevant to water management, these forecasts are often underutilized in management decisions. Based on findings from an AMS workshop in April 2018, this study analyzes how the forecasting and water resource communities could work together to improve water resource management across the US. Opportunities can be framed in terms of three main components:

(1) Advances in forecasts to meet the needs of water resource managers. Notably, the potential for improved decision making is not equally distributed across water management objectives, regions, and stakeholder groups. Improvements in spatial resolution would support planning for individual watersheds and advances in sub-seasonal to seasonal forecasts would help with drought management. Inclusion of impacts of upstream dam regulation to increase the accuracy of forecasts for heavily regulated rivers. To provide managers with more information about the full probability distribution of possible events, probabilistic forecasts are beneficial.

(2) Increased uptake and use of forecasts. Forecasts are most likely to be used when they are easily accessible, readily understood, highly skilled and relevant to management decisions. In addition, users need to have the necessary skills and information to make use of new and possibly more complex forecasts.

(3) Policies to support (1) and (2). Additional resources could support forecast improvement or the use of forecasts. New incentive structures could promote greater communication and collaboration among government institutions, scientists and service providers (e.g. National Water Center) across regions and sectors.Investments in quickly evolving communications technologies can promote forecast dissemination. Training forecasters and water resource managers as well as supporting pilot studies and testbeds may ensure an efficient translation of experimental improvements into operations.

Greater collaboration among forecasters, water resource managers and policymakers would support these efforts. In addition, preparation to adaptively manage resources, roles, and responsibilities will allow us to capture the benefits of advances in future forecasts and address new challenges that emerge over time.

1. Introduction

In providing water resource managers with information about inflows to reservoirs, weather and hydrologic forecasts can reduce flooding risks and impacts. Floods are one of the most common natural disasters in the United States (US), resulting in billions of dollars of damages annually.[1] Given these staggering costs, even small mitigation of extreme floods can have large benefits. For example, in 2017, Oroville reservoir operators in California suddenly released water to avoid the dam from overtopping, which required the evacuation of 188,000 people.[2] In 2011, rapid snowmelt and heavy rainfall contributed to devastating floods on the Missouri River which resulted in over $2 billion in damages and five fatalities.[3] While it is not possible to eliminate the risk of these disasters, advances in forecasting to support water resources management can help to minimize the consequences.

Forecasts have become more skilled at temporal and spatial scales relevant to water management. However, these forecasts are underutilized in water resource management (WRM) decisions for are a number of reasons**.** First, water managers may not be aware of the forecasts available, the skill of these forecasts and how the forecasts could be beneficial to decision-making. Even if they are aware of possibly useful forecasts, there may be institutional or legal impediments to the use of the forecasts. In some cases, available forecasts may not match the specific needs of water managers.

Forecasts have become more skilled at temporal and spatial scales relevant to water management.

On April 3-4, 2018 the AMS Policy office convened a workshop called "Translating advances in forecasting to inform water resources management" in Washington, DC to bring together weather and hydrologic forecasters, water resource managers, academics, and policy experts to discuss these issues. Speakers were chosen to represent agencies at the federal, state and local level, academia, private industry, and the US congress.

Greater communication and collaboration among members of the meteorology, forecasting, and water resource communities could help improve management of water resources. Here, we present the key findings of the workshop. In particular, three approaches to improving WRM were discussed: (1) improve weather and hydrologic forecasts; (2) increase the uptake and use of forecasts; and (3) promote policy actions to

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[1] http://www.nws.noaa.gov/hic/index.shtml

[2] https://www.washingtonpost.com/news/morning-mix/wp/2017/02/13/not-a-drill-thousands-evacuated-in-calif-as-oroville-dam-threatens-to-flood/?noredirect=on&utm_term=.d467aea3a085

[3] https://www.weather.gov/media/publications/assessments/Missouri_floods11.pdf
https://www.gao.gov/assets/670/665763.pdf

support (1) and (2). First, we examine the wide-range of groups involved in water resources management in the US as well as the status of current forecasting efforts. We then discuss opportunities for improvement and conclude with a summary of these findings.

2. Background and Current Challenges

a. Water Resource Management in the United States

Reservoir managers often must meet a diverse array of objectives including, but not limited to, supplying water, flood control, ecological flows, recreation, hydropower, and meeting water quality standards. These objectives can be in conflict when operators make management decisions. For example, hydropower is produced when water is released from a reservoir, but release of too much water could jeopardize supply for future uses or negatively impact ecosystems downstream. If drought is of concern, managers may want to keep a reservoir as full as possible, however, a full reservoir is not useful for mitigating flood risk. For example, But when an unexpected large storm arrived, the urgent need to release water resulted in the crisis.

Complicated laws and regulations govern WRM in the US: water rights differ between the Western and Eastern US and many agencies and Congressional committees are involved in forecasting and managing water. The number of groups focused on WRM reflects the importance and many uses of water. In the US, more than 10 federal agencies share responsibility over WRM. For example, the US Army Corps of Engineers (USACE) manages infrastructure, particularly dams and reservoirs primarily in the Eastern US, and is focused on flood control. In the West, the Bureau of Reclamation manages reservoirs for the provision of water supply and relies on weather prediction on various time scales. Additionally, National Oceanic and Atmospheric Administration (NOAA) provides observations, develops models, generates forecasts, and funds research. The US Geological Survey (USGS) gathers and maintains data for nearly 8,000 stream gages and over 24,000 crest gages across the country. These data are complemented by other sources such as the National Aeronautics and Space Administration (NASA) GRACE mission, which detects changes in the Earth's gravitational field to approximate information on groundwater. A new GRACE follow-on mission is scheduled to launch later this year.

As part of the National Weather Service, thirteen regional River Forecast Centers are tasked with synthesizing data from USGS stream gages, snowpack measurements, reservoir levels from USACE, and precipitation estimates from numerical weather predictions to predict river flows across the US. These centers have regional knowledge critical to the creation of accurate forecasts at the appropriate time scales for the region (generally 3 days in the East and 10 days in the West). Combining data from NOAA, NASA and USGS is also the basis for additional model predictions and products such as the National Integrated Drought information System.[4]

Local, state and regional entities are involved in many management decisions. Many of these agencies look to groups outside of the the government for information and management support, including private companies, academic institutions and NGOs. Private companies are hired by some water districts to develop tailored forecasts for a specific region or river basin. Academic researchers develop new modeling approaches, advance forecast skill, and sometimes highlight institutional challenges in uptake of forecasts. NGOs can play a crucial role in representing stakeholders, highlighting issues and communicating between other organizations and agencies.

b. Use of forecasts in Water Resource Management

Traditionally, short term hydrologic and weather forecasts have been deterministic, i.e. they consisted of one simulation of future conditions. However, over the last decade, the growth of computational resources has enabled probabilistic predictions of precipitation and streamflow. Probabilistic forecasts are created either by running a single model multiple times with different initial conditions or by grouping forecasts of different models. These ensembles of simulations produce a range of possible future outcomes, which can be used to calculate the uncertainty in the prediction or the probability of particular events. Quantifying the likelihood of very extreme outcomes is critical to decision-makers as these scenarios might require immediate action. Beyond two weeks, the forecast skill of traditional weather models has often proved inadequate for water resource managers to incorporate into their decisions. As a result, deterministic forecasts are well suited to short-term emergency management decisions but less useful to long-term planning. Subseasonal to seasonal (S2S) forecasts (2 weeks to 2 years) rely on sources of climate predictability such as teleconnections, snowpack, soil moisture, and the state of stratosphere. These forecasts do not predict the state of the earth system on a given day, but provide statistical information about the likelihood of a given event over a given time window. For example, seasonal forecasts can not predict the temperature on a particular day in the future, but the tendency for warmer temperatures in the upcoming months.

Quantifying the likelihood of very extreme outcomes is critical to decision-makers.

Currently weather and hydrologic forecasts are used to varying degrees by different water managers. The report "Weather forecasts are for wimps"[5] described a slow uptake of new forecasts by risk-averse water managers. The authors conclude that the high stakes of water management decisions hinder the experimentation needed to adopt new innovations. As a result, forecasts intended for use by water managers need to

[4] https://www.drought.gov/drought/

[5] Rayner, S., Lach, D. & Ingram, H. Climatic Change (2005) 69: 197. https://doi.org/10.1007/s10584-005-3148-z

demonstrate high skill before they will be considered for adaptation by the WRM community. Fifteen years later, a follow-up study[6] found that, in most cases, the adoption of forecasts was more widespread, but generally limited to short term weather forecasts. Additionally, water management organizations were still trying to balance the importance of local expertise with the use of externally developed models. While some organizations rely heavily on forecasts, USACE has a policy to limit most decisions to “water on the ground”, specifying that most “operations are not authorized to be informed by externally prepared forecasts that incorporate precipitation”.[7] Differences in forecast use across agencies reflects regional differences and distinct missions of these groups.

3. Opportunities

There are opportunities for the WRM, forecasting, and policy communities to promote the translation of forecasts to improve WRM. Based on discussions at the workshop, we describe how forecasts could be improved to support WRM needs (Section 3.1), ways to promote uptake of forecasts (Section 3.2), possible approaches to support the creation of forecasts appropriate to user needs (Section 3.3), and ,finally, opportunities for policy to support these efforts (Section 3.4).

3.1 Opportunities to improve forecasts

While there are a wide array of opportunities to improve forecasts, advances are limited by the quantity and quality of observations, available computational resources and scientific progress. In the following section, we outline how advances in forecasts might be able to better meet the specific needs of water resource managers given sufficient resources.

a. Use probabilistic forecasts

Traditionally water resource managers have used deterministic predictions of precipitation and streamflow. Increasingly, multi-model composites and ensembles, or multiple sets of forecasts, are becoming common as water resource managers have realized the value of these types of approaches. On time scales beyond two weeks, large ensemble predictions are less common due to their often prohibitive computational costs. Given the diversity of management options and the importance of preparing for extreme outcomes, water resource managers are uniquely positioned to take advantage of the additional information contained in probabilistic forecasts.

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[6] Lach, Denise & Rayner, Steve. "Are Forecasts Still for Wimps?" *Journal of the Southwest*, vol. 59 no. 1, 2017, pp. 245-263. *Project MUSE*, doi:10.1353/jsw.2017.0013

[7] P 45 https://www.usace.army.mil/corpsclimate/CCAWWG/short_term_WMD/

b. Improve seasonal and sub-seasonal forecasts

Drought management, planning agricultural operations, and meeting the water needs of ecosystems requires information on time scales from weeks to many months. While significant progress has been made, the skill of sub-seasonal and seasonal forecasts (Figure 1) is still often inadequate to meet the needs of the water resource managers. Yet, awareness of the need to improve precipitation forecasts, in particular on the seasonal and sub-seasonal forecasting timescale, is growing. There is now an annual workshop on the topic[8] and an international joint project of the World Weather and World Climate Research Programmes, called subseasonal to seasonal prediction (S2S), aims to bridge the gap between short term weather forecasts and seasonal predictions begins its second phase in 2019. Domestically, NOAA supports SubX (Subseasonal experiment), a climate testbed, which compares the skill of seven global models on forecast lead times of 3-4 weeks in advance. The project consists of hindcasts for the last 17 years and real-time predictions over one years. However, the funding for SubX is currently in a 1-year no-cost extension phase and funding beyond the summer of 2019 is uncertain.

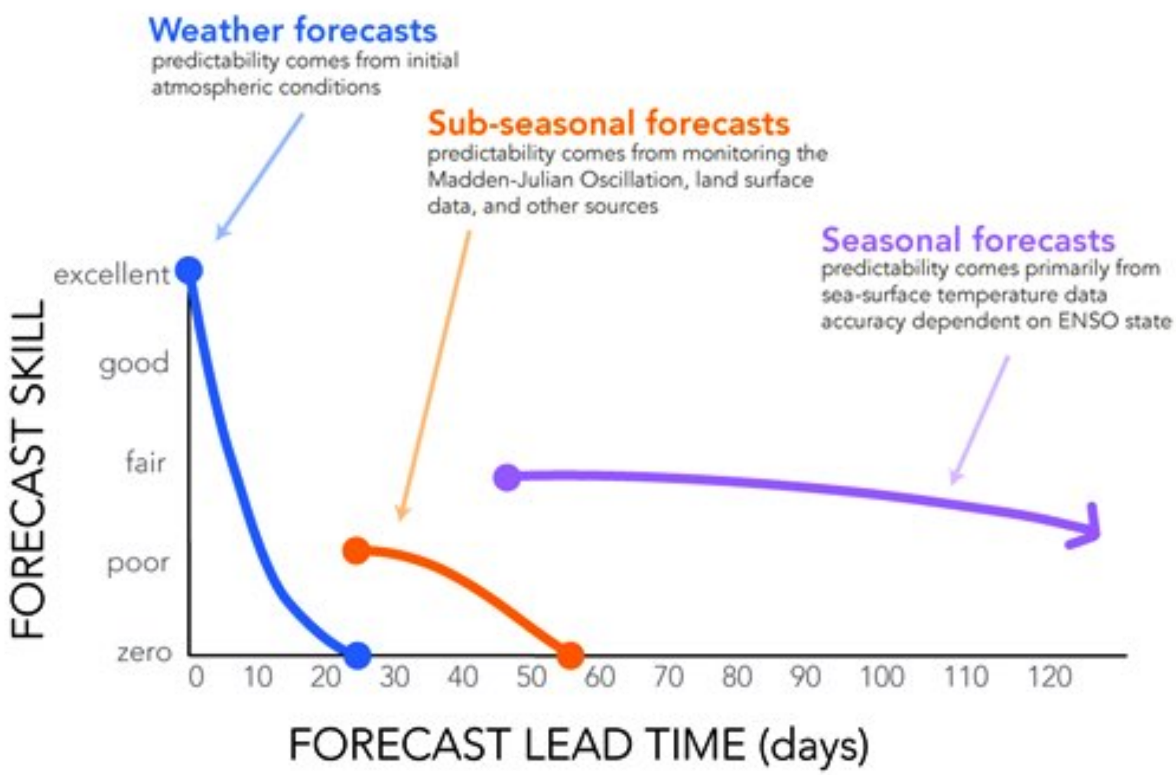

Figure 1: This graphic is a qualitative estimate of forecast skill based on the lead time of the forecast's issuing. In addition to the differences in the sources of predictability noted in the graphic, there are also differences in the nature of the forecasts. Weather (short-term) forecasts tend to be deterministic (e.g. the temperature will be 85°F today). As forecasts move into longer-range timescales, the methods and

[8] http://www.westernstateswater.org/improving-sub-seasonal-to-seasonal-s2s-precipitation-forecasting-to-support-water-management-decision-making/

data that go into the forecasts change, and so the nature of the forecast also changes. A greater level of uncertainty must be factored in to sub-seasonal and seasonal forecasts. So, instead of predicting specific weather events, the longer-range forecasts typically predict climate using probabilities, like the chances of a season being hotter, cooler, drier or wetter than average. Based on feedback from climate information users, researchers are also developing forecasts that predict other parameters, like the frequency of rainfall events over a season. Therefore, saying that a sub-seasonal or seasonal forecast has good skill does not mean it can accurately predict daily weather weeks or months ahead of time, but rather that it does a good job of predicting weather averages or statistics on weekly to seasonal scales over the course of the season is going to deviate much from average. Infographic adapted by Elisabeth Gawthrop from figure by Tony Barnston. Source: https://iri.columbia.edu/news/qa – subseasonal – prediction – project/.

c. Improve spatial resolution

Improvements in spatial resolution of both precipitation and hydrological forecasts are critical to support improved water resources management. To base decisions on precipitation forecasts, water resources managers need to know in which river basin precipitation will fall. Achieving this level or accuracy is difficult in models of the entire US and models for individual watersheds are not available everywhere. The National Water Model[9], created by the new National Water Center, represents the first high-resolution model at a continental scale, combining meteorological inputs with hydrologic and land surface data for nearly every watershed in the continental US. The goal is to produce street level forecasts for streams, coasts and, eventually, water quality using a single model. Off to a promising start, verification and evaluation of the model across the US will promote trust in the skill of the model and illustrate utility of the model for WRM and flood preparedness.

Future models need to incorporate real-time information on the operation of upstream dams.

d. Account for regulation of upstream flows

There are nearly 84,000 dams across the US[10], many of which are used to regulate streamflow. As a result, river flow can depend on human decisions upstream. At the moment, state-of-the-art models do not simulate the decisions of dam operators or other human impacts such as water withdrawals and transfers. To accurately reflect flow patterns, future models need to incorporate real-time information on the operation of upstream dams to capture complex feedback loops between water availability and human behavior. While models might never be able to fully capture the full breadth of all human impacts, analysis of historical decisions based on flows and weather forecasts might help to constrain the likely actions of dam operators and thus improve forecasts of flows on heavily regulated rivers. If successful, similar approaches could be used to represent other human influences on streamflow such as water withdrawals or water transfers.

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[9] http://water.noaa.gov/about/nwm

[10] https://www.fema.gov/media-library-data/20130726-1849-25045-6913/02_hydrosafetydam_ch_2_4.pdf

e. Tailor model development to the needs of stakeholders

Perhaps the most important factor in developing new forecasts is that they be tailored to the requirements of users. When there are mismatches between the information that is available and the specific needs of water resource managers, forecasts remain unused. However, developing forecasts for specific users in mind could shift resources away from more general improvements or make forecasts less relevant to other stakeholders.

The previous sections outlined some of the most pressing information needs of water resource managers. Addressing these needs will require improved observations, better scientific understanding and substantial computational resources. Therefore allocating resources efficiently becomes a difficult task as demonstrated by the tradeoffs scientists face in the development process. Increasing the spatial resolution or the time horizon of a model will naturally come at increased computational costs. The same is true for an increased number of ensemble members to improve uncertainty quantification or increased model complexity. The value of each model improvement will depend on stakeholder needs.

Meeting the needs of water resource managers involves difficult tradeoffs between spatial and temporal resolution, model complexity and uncertainty quantification.

For example, a dam operator in a region with many small watersheds might prefer increased resolution over improvements in modeling human decision-making. In contrast, a manager located downstream of many dams might be more interested in trying to capture the human impacts upstream. For water managers in arid climates, their main concern might be improving sub-seasonal to seasonal time scales to manage the risk of drought.

As a result, meeting the needs of water resource managers involves difficult tradeoffs between spatial and temporal resolution, model complexity and uncertainty quantification. The National Water Center produces extremely high-resolution forecasts for the entire continental US. As a result, ensemble predictions have been prohibitively expensive thus far and validation for water resource management has been less of a focus. In contrast, the SHARP model[11] prioritizes ensemble size over spatial resolution and coverage. This model is used to produce ensemble predictions of individual watersheds without the ability to predict stream flows across the country.

3.2 Opportunities to promote use of forecasts

Society will only benefit from advancements in forecasts if they are used effectively. Next, we describe a number of opportunities to support uptake of forecasts.

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[11] https://ral.ucar.edu/projects/system-for-hydromet-analysis-research-and-prediction-sharp

a. Improve dissemination of forecasts
Ensuring that forecasts reach all of the potential users and stakeholders is a challenge given the diversity and breadth of groups working on WRM. Improved dissemination would not only reach a larger number of users and could help additional stakeholders learn about and take advantage of existing forecasts. In addition, new hydrologic forecast approaches developed for one region might be useful for informing improved forecasts elsewhere in the country. Thus dissemination of forecast strategies more broadly also has the potential to support advancements in forecasts across a wider array of regions.

In addition to promoting use of existing forecasts, there is also a need for water resource managers to have a strategy for updating their operations when improved forecasts become available. Workshop participants were enthusiastic about opportunities for sharing of best practices and new forecasting approaches. In conversations leading up to the workshop, multiple managers and forecasters brought up the probabilistic hydrologic forecasts developed by Jim Porter to manage New York's complex system of reservoirs. A more formalized way for these groups to share their techniques could help promote use in other regions.

b. Ensure water managers get the most from forecasts
Water managers must have an in-depth understanding of forecasts before deciding to use them to inform decision-making and operations. Providing managers with regular opportunities to learn about how these forecasts are developed will likely promote uptake. For example, for water managers not be accustomed to using probabilistic forecasts, training and background in probability and statistics will help them take advantage of the additional probabilistic information.

Improved dissemination could help additional stakeholders take advantage of existing forecasts.

On the other hand, forecasters will need to improve their communication skills to spread increasingly complex forecasts products. As forecasts include more information about the likelihood of different scenarios, it will be easy to overwhelm or confuse end users instead of supporting better decision making. he National Weather Service is looking to social science to improve its communication of warning and watches and similar efforts may be needed to translate new streamflow prediction into better decisions.

c. Validate forecasts and communicate skill clearly
Water consumers expect clean, plentiful water every time they turn on the tap, with no interruptions in service or water quality. Because water resources agencies must meet very high standards of reliability, managers will only use forecasts, if they are confident in the skill of the prediction. Careful validation of forecasts for the region in which it will be used and clear communication of forecast skill can support uptake of skillful forecasts. Ongoing evaluation of forecast skill would allow for continued assessment of models and support user trust in the forecasts. In addition, appropriate representation

of forecast uncertainty can help water managers decide when the forecast is useful or not for a given management decision.

3.3 Policy opportunities

There are a number of ways in which the policy community can support the efforts detailed in the previous sections. The list below details some opportunities discussed at the AMS workshop and should not be viewed as an exhaustive list of all possible policy options.

a. Provide resources to support the above opportunities

Section 3.1 detailed the varied information needs of water resource managers. Meeting these needs will require continued investment in gathering observations, developing more advanced models and expanding computational capabilities. While many of these observations are also necessary for the development of weather prediction models, additional data on streamflows, land-use, groundwater and others are needed to inform WRM. Additionally, the need for high-resolution forecasts on many different time scales may require significant computational and staffing resources. Finally, as forecasts become more advanced and used by a wider range of stakeholders, the communication of forecasts will grow more complex. Resources to support training of forecasters to tailor their products to the information needs and technical skills of users could promote the widespread uptake of new forecasts.

Given the high stakes of WRM decisions, the WRM community tends to be risk-averse.

Given the high stakes of WRM decisions, the WRM community tends to be risk-averse. Thus, basing WRM decisions on new models will require extensive testing and evaluation. Support for pilot studies and testbeds could help to identify promising tools early in the development while minimizing the risk of negative consequences. In the later stages of model development, forecasts will need to be evaluated extensively to demonstrate the value and reliability of the new tools. As the performance of many models depends on the region or climate for which they were developed, it will be necessary to test models under a variety of circumstances.

b. Incentivize greater communication and collaboration

Institutionalizing the exchange between government agencies (federal, state and local), as well as members of the private sector, NGOs and academia could help support improved sharing of research results and best practices. This could come in many forms such as large conferences for many stakeholder groups or more targeted workshops. Online resources and platforms for collaboration might be a cost effective way to reach more remote areas.

Additionally, co-location of offices of different agencies can lead to greater communication and collaboration. Increased opportunities for researchers from academia and government agencies to coordinate research efforts could help to promote the transition of advances in forecasts from basic research to operational use.

Awareness of the need for interagency collaboration and co-location prompted creation of a National Water Center which has brought together NOAA, USACE and USGS employees in Tuscaloosa, Alabama. As part of growing efforts to obtain user feedback on forecasting models, the National Water Center has conducted stakeholder focus groups to gain feedback on their new National Water Model.

Finally, leveraging the large number of organizations in WRM, there may be opportunities to grow collaborations of the public sector with the private, academic and non-government organizations. If successful, these partnerships could bring additional resources and expertise to WRM. Furthermore, diverse groups of actors are more likely to represent the wide range of stakeholders and thus, increase the chances of widespread adoption and success. An effective dialogue among groups can promote information exchange, help avoid misunderstandings, identify best practices, and enable scientific advancement. One potentially valuable AMS role is to serve as a neutral convener, which could support future collaboration between the forecasting and WRM communities.

c. Develop a vision for the future of streamflow forecasting

Currently forecasters at RFCs manually run forecast models and adjust forecast results based on their knowledge of the model strengths and weaknesses as well as the specifics of local watersheds, demands and other factors. Including human judgement to tailor model results is called “in-the-loop” prediction and generally improves streamflow forecasts. It is often necessary for the operational use of these forecasts. The downsides of this approach are (1) it relies on human manipulation which can be subjective and slow; (2) it can be difficult to evaluate models because it is hard to separate the human changes from the model performance. For example, a popular way to assess the quality of weather model improvements is to produce forecasts of events in the past (hindcasts) and compare the performance to the model, which was used at the time. This comparison is complicated for streamflow predictions if the skill of the prior model depends on the human forecaster, who adjusted the model. Some newer models, such as the National Water Model, do not rely on human adjustments (over the loop predictions). The hope is that these models could free resources to allow forecasters to focus on forecast dissemination and model development. However, if over the loop predictions become the new standard, it could dramatically change the role of forecasters. Thus, implementing such a drastic change will require careful evaluation of the tradeoff between the added skill of human forecasters and the advantages of over-the-loop predictions. Local testbeds might provide the data necessary to better understand the impacts of over the loop predictions.

d) Leverage the strengths of private and public sectors

As the physical and anthropogenic inputs to water resource management are as diverse as the goals and priorities of managers, there is a growing need to work through the tradeoffs outlined above and to tailor forecasts to individual (groups of) stakeholders.

However, this process may require additional resources, which might otherwise be used to improve nationwide forecasts. A successful public-private partnership could combine countrywide model development with the flexibility and market efficiency of private companies to serve as many end users as possible.

For example, companies could use publicly available forecasts and measurements as well as privately-owned data to extract as much information as possible to derive the best water resource management plans for a given watershed. Consulting companies are already regularly hired by local and state agencies to fill the gap between available forecasts and the specific needs of water managers. As more data becomes available, models become even more complicated, and stakeholders diversify, opportunities for the private sector will likely increase. In this sense, the private sector might be able to add value to existing data and predictions, which are typically provided by government agencies. In fact, a recent report by the National Weather Service[12], highlighted the need for frequent engagement between the public and private sectors to leverage the large number of emerging technologies.

Opportunities for the private sector will likely increase.

e) Inform implementation of laws and regulations

Finally, policy-makers can use existing laws and regulations to advance the use of forecasts in WRM. To ensure the best use of resources, policy-makers could review approaches to WRM by different agencies and clarify responsibilities. This process has a greater likelihood of success if it draws on information from all stakeholders. In 2017, Congress passed the Weather Research and Forecasting Innovation Act ("Weather Act"), which includes two sections related to this issue. First, it specifically instructs NOAA to improve its subseasonal and seasonal forecasts. As discussed previously, better predictions on these time scales are critical to effective WRM, particularly in arid regions. Second, the act calls for an increase in "impact-based decision support services", illustrating that success of a forecast is not only measured in skill scores, but also in how it supports decision-making and helps communities. A successful translation of hydrologic and weather forecasts into better WRM decisions could exemplify the implementation of this part of the law.

Beyond legislation at the federal level, there are opportunities for members of the forecasting and water management communities to inform policy-makers at all levels of government about their needs and how to address them. This input from stakeholders and affected communities can lead to seemingly small changes in laws and rules with potentially large impacts. Finally, knowledge of WRM could help communities to communicate their needs to policy-makers more effectively.

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12 https://www.weather.gov/media/about/WaterIndustryAnalysisReport2018_July%2023_2018_FINAL.pdf

4. Conclusions

This study highlights a number of opportunities to increase use of existing and future forecasts in Water Resource Management. Efforts to advance forecasts, promote forecast uptake, and tailor these forecasts to the needs of water managers are likely to result in improved water resource management. There are also policy opportunities, such as supporting research and piloting efforts with additional resources and providing incentives for greater collaboration and communication among these groups. The Weather Act and the National Water Center indicate political support for these efforts.

To support translation of advances in forecasting with the goal of informing water resources management, the study finds the following opportunities. The recommendations are not ranked and do not consider available resources or political feasibility.

1. Tailor forecasts to water manager needs in a given location

2. Improve forecasts:

    - Increase use of probabilistic forecasts to provide managers with more information about the full probability distribution of possible events and give them a better sense of uncertainty.
    - Advance sub-seasonal to seasonal forecasts to support management of water resources at longer time scales (2 weeks to 2 years).
    - Include impacts of upstream dam regulation to increase the accuracy of forecasts for heavily regulated rivers.
    - Increase spatial resolution of model forecasts to improve planning for individual watersheds.

3. Promote the uptake of forecasts:

    - Improve dissemination of forecasts including better communication of existing forecasts and sharing of successes across regions.
    - Ensure users have the necessary skills and information to make use of new, more complex forecasts.
    - Validate forecasts and communicate skill clearly to demonstrate value to risk-averse stakeholder groups.

4. Promote a policy framework to support these efforts. This could include:

    - Providing resources for forecast improvement (observations, science, computational capabilities) or the use of forecasts (enhancing research to operations; communication; collaboration; and training of water managers and forecasters).

- Incentivizing greater communication and collaboration among government institutions, scientists and service providers (e.g. National Water Center) across regions and sectors.
- Identifying opportunities to most effectively implement the Weather Research and Forecasting Innovation Act of 2017 and remaining unmet needs.
- Supporting engagement of forecasters and stakeholders in policy process.

There is great potential to use hydrologic and weather forecasts to improve water resources management. Enthusiasm for the AMS workshop which informed this study illustrates that this is a topic of interest among a wide range of forecasters, academic institutions and water resource managers. The workshop also illustrated the need for continued conversations between these groups to future explore strategies to address these challenges and opportunities. Capitalizing on the value of forecasts can help us manage our nation's water resources effectively and minimize the risk and damages of future extreme floods and droughts.

Capitalizing on the value of forecasts can help us manage our nation's water resources effectively.

Appendix: Workshop Agenda

The **American Meteorological Society** presents:

Translating Advances in Forecasting to Inform Water Resources Management

WHEN: April 3rd – April 4th, 2018

WHERE: 1200 New York Avenue NW, Washington, DC 20009

Tuesday April 3, 2018

7:45 AM Registration and light breakfast

8:30 AM **Welcome**
Paul Higgins, Director, AMS Policy Program

8:35 AM **Overview**
Annalise Blum, Postdoctoral fellow, AMS Policy Program and Johns Hopkins
Andy Miller, Postdoctoral fellow, AMS Policy Program

8:45 AM **Operations: State of the art forecasts and their use in water management**
Ron Anderson, Lower Colorado River Authority
Rob Shedd, Mid-Atlantic River Forecast Center
Steve King, Northwest River Forecast Center
Cherie Schultz, Interstate Commission on the Potomac River Basin

9:45 AM **Discussion**

10:30 AM Break

11:00 AM **Keynote: The role of the National Water Center**
Peter Colohan, National Water Center

11:30 AM **Discussion**

12:00 PM Networking lunch

1:00 PM **How could forecasts be more useful to water managers?**
How can decision-making processes take advantage of available forecasts?
Kenneth Nowak, Bureau of Reclamation
Jim Porter, NY Department of Water
Curtis Jawdy, Tennessee Valley Authority

1:45 PM **Discussion**

2:30 PM Break

3:00 PM **Looking to the future I: Given advancements in modeling, how do we expect forecasts to improve?**
Sarah Kapnick, Geophysical Fluid Dynamics Laboratory, NOAA
Andrew Robertson, Columbia University
Bart Nijssen, University of Washington

3:45 PM **Discussion**

4:30 PM End of Day 1

<u>Wednesday April 4, 2018</u>

8:00 AM Light breakfast and networking

8:30 AM **Review of yesterday**
Bill Hooke, Associate Executive Director, AMS Policy Program

8:45 AM **What are the policy challenges and opportunities in translating forecasts to inform water management?**
Betsy Cody, National Socio-Environmental Synthesis Center (SESYNC)
Jeanine Jones, Western States Water Council
Sara Gonzalez-Rothi, Senate Committee on Commerce, Science & Transportation

9:30 AM **Discussion**

10:15 AM Break

10:45 AM **Looking to the future II: New data to meet information needs of water resource managers**

Julie Kiang, U.S. Geological Survey
Dan Sheer, HydroLogics
Kristi Arsenault, Science Applications International Corporation

11:30 AM **Discussion**

12:15 PM **Synthesis and conclusion**

Andy Miller and Annalise Blum, Postdoctoral fellows, AMS Policy Program

12:30 PM Workshop concludes

2:30-4:00 PM Hill briefing with Betsy Cody, Sarah Kapnick, Steve King, and Dan Sheer and moderated by Annalise Blum and Andy Miller