OPPORTUNITIES FOR FORECAST-INFORMED WATER RESOURCES MANAGEMENT IN THE UNITED STATES

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Weather and hydrologic forecasts can help us manage our nation's water resources more effectively by providing advance warning of large storms, extreme floods, or prolonged drought conditions. As these forecasts become increasingly accurate, their use can inform risk mitigation strategies. Societal benefits associated with these advances will only be realized, however, if the forecasts are used in management decisions.

Forecasts that do not match the needs of a specific water manager may remain unused. While each manager would prefer a tailored forecast, resources constrain production of such forecasts, which are less likely to be relevant to a wide range of stakeholders. Even forecasts that provide actionable, regionally relevant information may remain unused if institutional, legal, or policy impediments exist or if the potential usefulness of the forecast is not evident to water managers.

Increased communication and collaboration among members of the meteorology, forecasting, and water resource communities could help improve management decisions. On April 3–4, 2018 the AMS Policy Program convened a workshop in Washington, D.C., titled, "Translating Advances in Forecasting to Inform Water Resources Management." The workshop brought together nearly 100 weather and hydrologic forecasters, water resource managers, academics, and policy experts to discuss the integration of forecasts into decision-making to support more informed Water Resource Management (WRM). Here, we identify and describe three opportunities to improve WRM through forecasts: 1) improve forecasts, 2) promote use of forecasts, and 3) support policies that further these efforts.

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OPPORTUNITIES TO IMPROVE FORECASTS. Water resource managers have diverse, and sometimes conflicting, mandates and objectives. These may include some combination of controlling floods, meeting water supply needs (quantity and quality), protecting habitat (i.e., ecological flows), promoting recreation, and enabling hydropower. With these objectives, managers can have complex information needs. There are a number of ways that existing forecasts can be advanced to meet these needs.

First, in contrast to deterministic forecasts, probabilistic approaches provide quantitative predictions and a likelihood of occurrence for the range of possible outcomes. Based on ensembles of simulations of a particular model or ensembles of different models, probabilistic forecasts can be particularly beneficial to the management of extreme events. In addition, water managers may be uniquely positioned to take advantage of the additional information contained in probabilistic forecasts given that water releases and transfers can be made gradually.

Second, despite continued research efforts, the accuracy or skill of subseasonal and seasonal forecasts is often inadequate to meet the needs of water resource managers. While some objectives of WRM (e.g., flood management) crucially depend on high-quality predictions over a period of days, providing appropriate amounts of water for agriculture and ecosystems as well as managing drought risk require information on the subseasonal and seasonal time scales (two weeks to two years). This is because, in many regions, water is provided by a few days of heavy precipitation, while droughts develop over long periods of time. Predictions beyond two weeks have improved by quantifying the effects of teleconnections, snow cover, groundwater, and other factors, but it is uncertain if and when these forecasts will be able to meet the reliability requirements of the water management community.

Third, water resources managers need forecasts with improved spatial resolution that can predict in which river basin precipitation will fall. Currently under development, the National Water Model (http://water.noaa.gov/about/nwm) is 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 United States. While progress on the National Water Model is promising, the Model is yet to be broadly incorporated into WRM operations.

Fourth, to obtain accurate estimates of water flow through many rivers, it is necessary to consider human impacts. With an estimated 84,000 dams across the United States, river flow often depends on human decisions made upstream. To account for upstream regulation of flows, future models will need to incorporate real-time information on the operation of dams to capture complex feedback loops between water availability and human behavior.

Finally, there are many opportunities to tailor forecasts to the needs of stakeholders. For example, the main concern of water managers in arid climates might be improving forecasts at subseasonal-to-seasonal time scales to manage the risk of drought. In contrast, a manager located downstream of many dams might be more interested in trying to capture the human impacts of upstream regulation. However, developing forecasts with specific users in mind could shift resources away from more general improvements or make forecasts less relevant to other stakeholders. Allocating resources to meet the needs of diverse water resource managers will, at least in some cases, involve trade-offs among different user needs, such as spatial and temporal resolution, model complexity, and uncertainty quantification.

OPPORTUNITIES TO PROMOTE USE OF FORECASTS. To realize the full potential for societal benefit from advancements in forecasts, these forecasts must be utilized in management decisions. We next describe a number of opportunities to support uptake of forecasts.

First, improved dissemination of forecasts could help stakeholders who are not currently using forecasts determine whether it would be beneficial to incorporate forecasts into their decision-making. As new approaches are developed for one region, there may be relevant applications to other regions. Participants of the AMS Policy Program workshop specifically highlighted the importance of identifying and taking advantage of opportunities for sharing best practices and new forecasting approaches.

As new forecasts become increasingly complex and used by a wider range of stakeholders, communication challenges will increase. To use forecasts to inform decision-making and operations, managers must understand these forecasts. On the other hand, forecasters will need to carefully communicate the skill and limitations of their forecasts. To address these challenges, coproduction of knowledge (i.e., including mangers in identification of priorities for forecast advancement, dissemination, and communication) and coapplication of knowledge (such as including forecasters in WRM decisions) are both promising approaches. However, if more complex forecasts need to be translated to a widening group of stakeholders, it might be beneficial to employ specialists and social scientists who have a deeper understanding of effective cross-group communication.

Because water resources agencies must meet very high standards of reliability, managers must be confident in the skill of a prediction before incorporating it into their decision-making process. Careful validation of forecasts and clear communication of forecast skill can support forecast uptake. Ongoing evaluation of forecasts would help to improve models and build trust from the operational end-user community.

POLICY OPPORTUNITIES. A number of opportunities for the policy community were discussed at the AMS workshop. First, greater provision of resources can support the options detailed above to improve forecasts and increase forecast uptake. Improvements in forecasts will rely on continued investment in gathering of observations, developing more advanced models, and expanding computational capabilities. To support increased uptake of forecasts, resources are needed to promote information sharing, communication training, and tailoring of forecasts to meet manager needs.

Given the high stakes of WRM decisions, water managers tend to be risk-averse. Thus, basing WRM decisions on the forecasts produced by new models will require extensive testing and evaluation. Support for validation pilot studies and applications in WRM could help to identify the most promising new developments. Ideally, these pilot studies can speed up the research-to-operation cycle without interrupting current operations. In the later stages of model development, forecasts will need to be evaluated extensively to demonstrate their value and reliability. As the performance of each model is likely to vary by region or climate, it will be necessary to test models under a variety of conditions.

Currently, forecasters at the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) River Forecast Centers manually run models and adjust forecasts based on their regional and modeling knowledge. Including human judgement to tailor model results, or "in-the-loop" prediction, generally improves streamflow forecasts and currently is necessary for operational use. The downsides of this approach are 1) it relies on human manipulation, which can be subjective and slow; and 2) it can be difficult to separate the human changes from the model performance for evaluation purposes. In contrast, "over-the-loop" models, such as the National Water Model, do not rely on human adjustments. This approach might free resources to allow forecasters to focus on other aspects of forecasting such as dissemination and model development. However, a change in the approach to forecasting will require careful evaluation of the trade-offs 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 such a shift.

There are also opportunities to strengthen relevant policies so that they incentivize greater communication and collaboration between forecasters and water managers. Institutionalizing the exchange between government agencies (federal, state, and local), 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. Additionally, collocation 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.

Additionally, partnerships between the public and private sectors, academia, and nongovernmental organizations could bring additional resources and expertise to inform WRM. An effective dialogue among these groups would promote information exchange, identify best practices, and enable scientific advancement. Given the success AMS has had serving as a neutral convener for the weather industry, there is an opportunity for AMS, or other NGOs, to do the same for the forecasting and WRM communities—possibly in collaboration with other organizations such as the American Water Resources Association.

As more data become available, models become even more complicated, and stakeholders become more diverse, opportunities for engagement of the private sector will likely increase. For example, companies could use publicly available forecasts and measurements as well as privately owned data to derive the best WRM 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. In this sense, the private sector can add value to existing data and predictions, which are typically provided by government agencies. In fact, a recent report by the NWS (www.weather.gov/media/about/WaterIndustryAnalysisReport2018_July%2023_2018_FINAL.pdf) highlighted the need for frequent engagement between the public and private sectors to better leverage the large number of technological innovations, including advances in sensors, crowdsourced data collection, and delivery of real-time services.

Finally, policymakers can build on existing laws and regulations to advance the use of forecasts in WRM. Complicated laws and regulations govern WRM in the United States: water rights differ between the western and eastern states, and many agencies and congressional committees are involved in forecasting and managing water. To ensure the best use of resources, policymakers could review approaches to WRM by different agencies and clarify responsibilities. In 2017, Congress passed the Weather Research and Forecasting Innovation Act ("Weather Act"), which includes two sections related to the focus of the AMS workshop. First, it instructs NOAA to improve its subseasonal and seasonal forecasts, which, as we have discussed, will inform effective WRM, particularly in arid regions. Second, the Weather 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.

Beyond legislation at the federal level, there are opportunities for the forecasting and water management communities to engage with policymakers at other levels of government. Input from stakeholders and scientists can lead to small changes in laws and regulations that have potentially large impacts.

CONCLUSIONS. With more advanced and relevant forecasts, water managers will be better able to manage our nation's water resources effectively and efficiently. The enthusiasm we experienced at the AMS workshop illustrates that use of forecasts to inform water management is a topic of great interest to a wide range of stakeholders and scientists. The findings of this workshop serve as a starting point to an important discussion. Ongoing conversations on this topic can support the application of forecasts to their highest potential, help water managers plan under uncertainty, and mitigate the risks of future floods and droughts.

For more information and policy reports, please reference the AMS Policy Program website at www.ametsoc.org/index.cfm/ams/policy/.

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