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INTRODUCTION TO A SPECIAL SECTION
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Special Section:
Earth and Space Science is Essential for Society

Key Points:
- Many of the most meaningful problems necessarily engage scientists from multiple fields to conduct rigorous interdisciplinary science
- Science is done to help people and consequently requires scientists to effectively communicate science advances to society
- Science is needed to objectively inform the policy process

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Celebrating hydrologic science: The "Science is Essential" collection

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Abstract *Water Resources Research* published nine commentaries in the AGU "Science is Essential" collection. The goal of these papers is to celebrate the advances in hydrologic science, to show how hydrologic science is essential for society, and to illustrate how hydrologic science has influenced policies. Here we provide a brief introduction to these papers, to encourage you to explore them in full.

1. Speaking Up for Science

Professor James Kirchner delivered the 2016 Langbein Lecture at the AGU Fall Meeting, concluding with an epilogue on the importance of science to society: "*Walter Langbein clearly believed that science should matter, and that science does matter in the real world. And in Walter Langbein's era that view was widely held by society as a whole.*"

Kirchner's comments were sober and direct: "*We now live in a much more cynical age. [. . .] Today, three centuries after the Enlightenment, we should not have to defend the case for rationality in public life. But we do have to.*"

Prof. Kirchner concluded his lecture with a call to action: "*As scientists we need to find a way to make ourselves heard, not as advocates for some political cause or another, but as advocates for a fundamentally rational public discourse, one that starts from the facts – not from what we might choose to believe – and then confronts the messy questions of what society should do. So if you were ever inclined to stand up, speak out, and make yourself heard, now would be an excellent time to do it.*"

Kirchner's remarks echoed a broader public movement to speak up for science. As part of AGU's support for the March for Science (Earth Day, 22 April 2017), *AGU Journals* decided to publish a special collection of invited commentaries to highlight how science benefits humanity (see *Special Section: Earth and Space Science is Essential for Society*). The goal was to showcase how research in the Earth and Space sciences makes a difference to society and people's lives.

2. Overview of the WRR "Science is Essential" Papers

The nine papers in the *Water Resources Research* "Science is Essential" collection celebrate advances in hydrologic science. The messages in these papers are compelling. Every one of them is brief in the reading, accessible, and packed with content.

2.1. Tetzlaff, Carey, McNamara, Laudon, and Soulsby [2017]: The Essential Value of Long-Term Experimental Data for Hydrology and Water Management

Tetzlaff et al. focus on the foundation of catchment hydrology, the long-term observational studies in research catchments. They present a number of compelling examples illustrating how hydrologic process understanding has been generated through comparing hypotheses to data, and how this understanding has been essential for managing water supplies, floods, and ecosystem services today. Tetzlaff et al. emphasize the primacy of data, to clarify how the water cycle "works," to quantify variability and change in hydrologic systems, to develop, refine, and test predictive models, and, more generally, to develop a more concrete understanding of hydrological processes that is necessary to support water resources planning and management.

2.2. Grant and Dietrich [2017]: The Frontier Beneath Our Feet

Grant and Dietrich summarize progress in the exciting new frontier of critical zone science. This research focuses on understanding the dynamic evolution of hydrologic, biological, and geomorphological processes in the Earth's thin "critical zone" that extends from the top of the vegetation canopy to the greatest depth of active groundwater and supports most of the terrestrial life on Earth.

Grant and Dietrich highlight exciting advances in understanding this zone and argue that, fundamentally, critical zone science is about the interplay of water and life. Critical zone science provides answers to questions such as how landscapes evolve, why trees grow where they do, and how the linkages among climate, topography, vegetation, soils, and bedrock dictate the storage and movement of water through the landscape. More generally, the authors emphasize that critical zone science provides knowledge to help maintain healthy forests, to sustain streamflow during droughts, and to improve landscape resilience to wildfires, floods, and hurricanes.

2.3. Belmont and Foufoula-Georgiou [2017]: Solving Water Quality Problems in Agricultural Landscapes: New Approaches for These Nonlinear, Multiprocess, Multiscale Systems

Belmont and Foufoula-Georgiou illustrate how sustained science and stakeholder involvement have transformed our understanding of water quality problems in the agricultural upper Midwestern U.S. Starting in 1992, attempts to improve water quality in the Minnesota River Basin (MRB) relied on taking land out of agricultural production and conventional sediment and nutrient reduction projects. However, after 20 years of restoration efforts, sediment and nutrient problems persisted. Research showed that while sedimentation from farm fields had indeed decreased, these sediment reductions were offset by an increase in sediment from near-channel erosion, due to an amplified hydrologic cycle attributed to climatic trends and extensive agricultural drainage practices.

The research team built a suite of reduced-complexity models that couple hydrology, sediment, and river ecology at the watershed scale to evaluate management alternatives with a diverse stakeholder group. The consensus document that emerged recommends developing detention basins and wetlands in targeted locations of the watershed to desynchronize peak runoff from different areas in order to substantially reduce channel erosion. This compelling success story shows how regional development can be achieved by combining interdisciplinary science, participatory stakeholder modeling, and a willingness to use science to inform policy and management decisions.

2.4. Lettenmaier [2017]: Observational Breakthroughs Lead the Way to Improved Hydrological Predictions

Lettenmaier presents two examples where recent advances in satellite and airborne observation capabilities are improving hydrologic predictions. The first example is large-scale drought monitoring over Africa, which can aid in planning humanitarian relief efforts. Lettenmaier shows that using bias-corrected satellite precipitation products to force a macroscale hydrologic model provides spatially explicit information on drought in data sparse regions. The second example is high-resolution (meters-scale) snow depth monitoring that substantially adds to the information available from sparse station networks in mountain regions. Such high-resolution snow products enable us to focus on the spatial scale of the dominant processes (e.g., topographic controls on snow accumulation and melt), opening opportunities to diagnose model errors and improve model physics. Lettenmaier argues that these new observations are revolutionizing our capabilities for hydrologic modeling and prediction, aiding farmers and water supply managers.

2.5. Scanlon, Ruddell, Reed, Hook, Zheng, Tidwell, and Siebert [2017]: The Food-Energy-Water Nexus: Transforming Science for Society

Scanlon et al. focus on the challenge of improving the affordability, reliability, and environmental sustainability of food, energy, and water for the growing global population. They review emerging interdisciplinary science efforts that are providing new understanding of how food, energy, and water production are intertwined, and they define key science needs to support coordinated food-energy-water management as a single system with multiple outputs. The major science advances in the last decade include new capabilities to estimate regional hotspots of food-energy-water scarcity, along with understanding the value of alternative food-energy-water policy options (e.g., increasing supplies, storage and transport, and conservation). Looking forward, Scanlon et al. argue that science advances will require interdisciplinary and international research partnerships: merging global analyses with regional-local analyses, merging model simulations with ground-based and satellite monitoring, and, importantly, incorporating human and institutional behavior in models.

2.6. Michael, Post, Wilson, and Werner [2017]: Science, Society, and the Coastal Groundwater Squeeze

Michael et al. scrutinize the societal problem of "the coastal groundwater squeeze," where potable freshwater is threatened by both contamination at the land surface and seawater intrusion at depth.

Like other hydrologic systems, the scientific challenges in understanding and predicting change in coastal aquifer systems involve grappling with both system complexity and limited data. The aquifer properties are heterogeneous and difficult to quantify; the hydrologic forcing operates across a range of different time scales, causing disequilibrium in the distribution of pressures and solutes; and the chemical and mixing processes depend on the geology, flow pathways, and hydrologic forcing in complex ways. Underlying these challenges is the dramatic influence of human activities on coastal aquifer systems.

Michael et al. argue that addressing the coastal groundwater squeeze requires both interdisciplinary research collaborations to advance understanding and prediction capabilities, and also (importantly) greater collaboration among scientists, policy makers, and the public to improve coastal zone management.

2.7. Celia [2017]: Geological Storage of Captured Carbon Dioxide as a Large-Scale Carbon Mitigation Option

Celia reviews the opportunities for geological storage of captured carbon dioxide (CO_2) as a way of reducing global CO_2 emissions to the atmosphere. The science advances in groundwater hydrology, where many decades of research have advanced our understanding of multiphase flow in porous media, have provided the capabilities to simulate different CO_2 injection scenarios.

The technologies evaluated by Celia are straightforward, at least in principle: CO_2 from large stationary sources is captured before being emitted to the atmosphere, and the captured CO_2 is then injected into deep geological formations. The risks of CO_2 injection include both the possibility of induced seismicity associated with elevated fluid pressures, as well as leakage of fluids to drinking water aquifers or the atmosphere.

Celia notes that the costs of carbon capture and storage are rather high, and a significant contribution to the carbon problem requires large-scale regional implementation of CO_2 capture infrastructure, including pipeline systems and multiple injection sites. Regardless, the technologies and political appetite for innovative carbon sequestration options continue to advance, highlighting the importance of research in the geosciences for creating a low-carbon energy future.

2.8. Sturm, Goldstein, and Parr [2017]: Water and Life From Snow: A Trillion Dollar Science Question

Sturm et al. focus their attention on the societal costs of disappearing snow cover. They point out that many societies around the world depend on snow for their water supply; that snow is declining in many mountain ranges throughout the world; and that snow research can provide actionable information to inform expensive societal decisions.

Sturm et al. quantify the economic cost of snow disappearance as follows: they note that a greater proportion of runoff will occur in winter, when it is useless for irrigation and therefore "lost to the ocean." They further consider that the out-of-season runoff will need to be replaced, and that there is a cost associated with replacing this water. Based on these premises, different alternatives for the price of water, and equations from environmental economics to define temporal trajectories of replacement costs, they find that the economic cost of snow disappearance in the western U.S. is potentially in the trillions of dollars.

Sturm et al. emphasize that such large societal costs make it imperative to improve how we monitor and predict changes in snow, and to forge close collaborations between snow scientists and environmental economists in order to explore alternative policy options for land and water management.

2.9. Kirchner [2017]: Science, Politics, and Rationality in a Partisan Era

Kirchner explores the role of science in providing the factual foundation for policy debates. Building on his Langbein Lecture (described above), he reflects on the role of science in the current partisan era. He quips: ". . . *the political process often uses science the way a drunk uses a lamppost: for support rather than illumination*." Kirchner is clearly concerned about the potential emergence of a postfactual society. He illustrates the value of respect for data through the case history of a discovery of toxic streamflow draining from an abandoned mine.

Kirchner also raises broader concerns regarding how scientists engage with the policy process. He reminds us that policy choices always involve the interplay between facts and values—that science can provide the factual basis for decisions, but what society does with those facts is a political issue. He argues that we must draw a clear line between a political process that distorts the facts, and one that reaches a conclusion that we dislike. Kirchner argues that activism for political causes will fuel the impression that our science has been slanted to suit our personal politics.

Kirchner's main message is to vigorously defend the essential role of science in a rational public discourse. Our chief responsibility, he argues, is to speak out loudly and proudly for science itself.

3. Consistent Messages

The commentaries published in *Water Resources Research* were prepared by leaders in hydrologic science, and we can see from the papers that leadership is derived from more than just knowing how to accomplish technical tasks or to design the perfect experiment. Rather leadership also comes from knowing why science is necessary. This fundamentally focuses research on those areas where disentangling complexity, confusion, and uncertainty are important to society. Across all of the articles are examples where science has illuminated facts pertinent to societal decisions about, and human needs for, water.

The commentaries contain several consistent messages. First, the commentaries emphasize that much science is done to solve difficult problems, and many of the most meaningful problems necessarily engage scientists from multiple fields to conduct rigorous interdisciplinary science. For example, *Grant and Dietrich* [2017] define interdisciplinary research as the hallmark of critical zone science. *Michael et al*. [2017] emphasize collaboration across hydrogeology, oceanography, biogeochemistry, engineering, economics, sociology, and policy as essential to advance the science of coastal groundwater. *Scanlon et al*. [2017] highlight interdisciplinary research as clearly critical to understand the complex linkages among food-energy-water systems. *Belmont and Foufoula-Georgiou* [2017] highlight the importance of collaborating with stakeholders.

Second, the commentaries highlight that science is done to help people and consequently requires scientists to *effectively* communicate science advances to society. For example, *Michael et al*. [2017] note that improved community knowledge of coastal groundwater concepts can increase community engagement in protecting coastal aquifers. *Tetzlaff et al*. [2017] emphasize the importance of encouraging "citizen science," e.g., involving the public in data collection efforts, to increase awareness of and appreciation for the importance of data and the process of discovery. More generally, the commentaries highlight the importance and intensification of science communication—many have been involved in science communication and outreach activities for years, and others have increased their involvement in these activities as a result of the changes in political and societal attitudes toward science. We hope that the commentaries highlight the importance of hydrological science for society and provide further motivation to improve links between science and society.

Third, and perhaps most important, the commentaries articulate the need for science to objectively inform the policy process. For example, *Sturm et al*. [2017] highlight the need to understand the value of the snow resource when exploring alternative policy options. In a very different example, *Celia* [2017] shows how decades of research on multiphase flow in porous media now provides the capabilities to simulate different CO_2 injection scenarios, and illustrates how the geosciences can offer possible solutions to the carbon and climate problem. *Belmont and Foufoula-Georgiou* [2017] show how science-informed policy can work in practice, where interdisciplinary science, participatory stakeholder modeling, and a willingness to use science to inform policy and management decisions all combined to define policy alternatives to improve water quality. In this last example, the participation of the scientists in the policy-making process helped stakeholders to more carefully frame questions.

The examples presented in the collected papers are only the tip of the iceberg. There are many other examples that could be mentioned—where hydrologic science is used to predict floods, quantify water supplies, and evaluate the fate of contaminants. Emerging scientific understanding is routinely used to help protect people's lives and livelihoods from natural disasters, ensure adequate access to drinking water, provide ample food, and resolve water conflicts. These commentaries highlight the value of good science as the foundation of decision making. They illustrate why science is worth doing, and why it is worth sharing.

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