DATA INTELLIGENCE FOR 21ST CENTURY WATER MANAGEMENT

A REPORT FROM THE 2015 ASPEN-NICHOLAS WATER FORUM

Duke
NICHOLAS INSTITUTE
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Celebrating 10 Years

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The Aspen Institute is an educational and policy studies organization based in Washington, D.C. Its mission is to foster leadership based on enduring values and to provide a nonpartisan venue for dealing with critical issues. The Institute has campuses in Aspen, Colorado, and on the Wye River on Maryland's Eastern Shore. It also maintains offices in New York City and has an international network of partners.

The Aspen Institute **Energy and Environment Program** provides nonpartisan leadership and a neutral forum for improving energy and environmental policymaking through values-based dialogue. The Program convenes strategic groups of experts from government, business, academia, and nonprofit organizations in dialogue structured and moderated for discussion, exploration, and consensus building. *www.aspeninstitute.org*

The Nicholas Institute for Environmental Policy Solutions at Duke University improves environmental policymaking worldwide through objective, fact-based research to confront the climate crisis, clarify the economics of limiting carbon pollution, harness emerging environmental markets, put the value of nature's benefits on the balance sheet, develop adaptive water management approaches, and identify other strategies to attain community resilience. The Nicholas Institute is part of Duke University and its wider community of world-class scholars. This unique resource allows the Nicholas Institute's team of economists, scientists, lawyers, and policy experts not only to deliver timely, credible analyses to a wide variety of decision makers, but also to convene these decision makers to reach a shared understanding regarding this century's most pressing environmental problems. *www.nicholasinstitute.duke.edu*

The 2015 Aspen-Nicholas Water Forum was the fourth forum in which the Aspen Institute and the Nicholas Institute have partnered. The first, in 2005, on water, sanitation, and hygiene in the developing world, produced *A Silent Tsunami,* which made a material contribution in advancing priorities in U.S. foreign assistance for basic water services. The report ultimately helped spur passage of the Paul Simon Water for the Poor Act. In 2011, the two institutions again joined together to host a one-day forum to take stock of progress, documented in *A Silent Tsunami Revisited.* The success of these endeavors provided the impetus for additional forums focused on water concerns in the United States.
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PREFACE

Data measurements in the 21st century are more likely to be made by phones or satellites than by chemists and geologists; data are no longer collected solely by scientists doing intentional data-collection. With the increased amount of data, we are now limited not by information, but rather by the ability to make sense of the vast quantities and types of information being generated. All of these data will be underutilized without the tools and analytics to harness the opportunities they create.

To understand the challenge that "big data" presents in the water sector and facilitate data integration to improve water management—a focus area prioritized during the 2014 Aspen-Nicholas Water Forum—the Aspen Institute's Energy and Environment Program and Duke University's Nicholas Institute for Environmental Policy Solutions focused the 2015 Aspen-Nicholas Water Forum on data intelligence for 21st century water management.

The Annual Aspen-Nicholas Water Forum serves as a platform for addressing domestic water challenges in the 21st century. This year's multi-day forum convened 50 executives, entrepreneurs, policy makers, and thought leaders, and focused on the new universe of big data and its impacts on the water sector, including how the emergence of large—but dispersed—amounts of data in the water sector can be used to improve the management and delivery of water for a more sustainable future.

This forum summary was written collaboratively by the Nicholas Institute for Environmental Policy Solutions at Duke University, the Aspen Institute, and our rapporteur, Dave Grossman, who helped distill and summarize the richness of the wide-ranging discussions. Though the authors have attempted to capture the ideas and sentiments expressed during the forum, not all views were unanimous nor were unanimity and consensus sought. Forum participants and sponsors are not responsible for its content.

We thank the following sponsors for their generous support of the forum: Intel Corporation, Water Asset Management, the Walton Family Foundation, Oak Ridge National Laboratory, National Renewable Energy Laboratory, National Association of Water Companies, and Gallo Wines.

Looking ahead, the Aspen Institute and the Nicholas Institute will continue to collaborate to develop forward-thinking pathways to address the state of the U.S. water system. The plethora of challenges in the U.S. water sector today—from the drought in California to the need for policy and market solutions that address water trading opportunities—will continue to be addressed through the Aspen-Nicholas Water Forum.

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EXECUTIVE SUMMARY

In May 2015, the Aspen Institute Energy and Environment Program and the Nicholas Institute for Environmental Policy Solutions at Duke University hosted the **Aspen-Nicholas Water Forum**, a roundtable discussion to address ongoing challenges to our water systems. The participants—50 thought leaders from the private sector, government, academia, and non-governmental organizations—represented expertise in finance and investment, utility management, federal and state policy, ecosystem management, environmental protection, technology, land use planning, energy, corporate water management, agriculture, and communications.

Participants explored the growing opportunity for data intelligence in water management and water quantity and quality issues worldwide. These challenges are inherently local and regional, and the diversity of local concerns, uses, conditions, and priorities means that any actions taken to address them will vary widely from region to region. Adding to the diversity of challenges is the fact that water systems do not exist in a vacuum, but rather are inextricably intertwined with energy and food systems, making the issues within each system potentially more complex, while also creating real opportunities for water savings. In many regions, including the United States, significant opportunities exist for water savings through price mechanisms, technological changes, communications efforts, and basic education; the opportunities for increasing water supply in the United States, however, are likely quite limited.

Understanding what water data we have, how we collect it, and how to standardize and integrate it may well be a prerequisite to taking action to address a wide range of water challenges. Unfortunately, we have significant gaps in our knowledge of how much water is available, how much water is needed and used, and how those quantities are changing over time, making it harder to determine how to allocate water among competing needs. The technology typically exists to get the data needed, and indeed, much of the data has been and is being collected, but there is a striking lack of synthesis and use of available data, particularly new types of data. In general, there is a lack of political will to fund data collection and synthesis activities, particularly at the federal level, suggesting a need for an external push by relevant stakeholders to advocate for increased funding for data-gathering and data synthesizing efforts.

Even with funding constraints, there are remarkable things happening in the world of water data. We are moving into a golden era of remote sensing hydrology, with satellites that can provide unique insights into freshwater availability and global water demand. New tools are taking existing satellite land cover and surface water data and making it more accessible to users for them to manipulate and analyze across scales from continental to the backyard. The agricultural sector is in the midst of a new green revolution in which remote sensing data, GIS (geographic information systems) modeling, and LiDAR (remote sensing technology that measures distance using light) are transforming farming and dramatically increasing efficiency, while those in the environmental conservation sector are using similar technologies to identify hotspots for restoration and best management practices. We may also be on the cusp of having very cheap, real-time water quality sensor technologies, which could be transformative across sectors. Low-cost water quality monitoring will bring a wave of data from citizen scientists, which could be used, among other things, to help detect polluting events, identify hotspots of pollution, or transform the temporal and spatial scale of water quality information.

People can be not only gatherers of water data but also producers of it, and intensive data research trials are underway on how people use electricity and water. Due to their general lack of capital, poor IT systems, and slow uptake of technologies, water utilities are not the ideal entities to manage these data or to convert them into actionable information; rather, that will be better done by third-party providers. Still, there are opportunities for water utilities to get value from this kind of data, including by finding meters they did not know they had, cutting demand at particular times, and using the cloud to achieve economies of scale. The foundation of a 'smart water grid' is an increased information infrastructure, and the basis of this will be greater amounts of information collected at the scale of individual water users. This type of data and synthesis is now becoming a reality at the pilot scale.

Although the public may produce a great deal of water data, many people and entities have little interest in sharing it. Farmers, in particular, are the largest users of water in the United States and collect enormous amounts of data about water application on their fields. Yet they are also highly resistant to making such data available for broader use. Water users are unlikely to make their data available if those data are intended to be used by governments to initiate enforcement actions against them or by the media to vilify them. Incentives for data sharing, such as financial gain, or methods to anonymize or consolidate data to a scale that is actionable beyond just regulatory enforcement may help unlock such sources of data.

For data to be truly useful, we must progress from data to information to knowledge to decision-making. Big data, and the analyses and visualizations that can be done with it, create opportunities to change the way the world looks at and acts on water—if the data are turned into information products and tools that are actionable and useful. Sometimes there are mismatches between data needs and availability, such as discrepancies between the available and the desired levels of resolution.

Conversations between data providers and the sectors that will apply the data need to continue, to help ensure the data and tools created are useful. This is particularly true for data generated by federal government research agencies.

Key to making big data actionable is harnessing, standardizing, and integrating the enormous amount of data we already have and continue to generate. A lot of data that are already available are only just beginning to be aggregated and organized, and such aggregation requires common data standards, which are lacking in the water sector. As a first step, a foundational baseline set of water standards, indicators, and measurements should be defined that reflect the core data on the state of our water system. Data standardization will then enable integration of data collected for different purposes, ranging from satellite data to data collected for local water management; social science data, while providing valuable and complementary context, will be challenging to integrate. At the federal level, it is as yet unclear which agency should be responsible for pulling the various datasets together, although the U.S. Geological Survey is well-positioned to serve this role for many types of water data.

Farmers, businesses, investors, and policymakers are all important audiences for data and data tools. Agriculture is by far the largest water user in the United States and globally. In dry years, when there is not enough surface water for use by farmers, aquifers get overdrawn as a source for agricultural water. There are many new players entering the intersection of agriculture and data, offering services and information about improving yields, how much water to put on a field, etc. As with other aspects of water data, good data in farming can be easily manipulated into actionable information that enables thoughtful analysis and better decisions. For most farmers, that means data are needed at the scale of an individual field. Many farmers collect at least some of the data they need—and would like more data from others at a useful resolution—but they often have policy reasons and other reasons (including strong distrust of cities and government agencies) for not sharing it.

Companies and investors are paying increasing attention to water as well, though water risks are not yet integrated into every core business function, operation, and decision. Leading companies are quantifying the value of water, assessing water risks in their processes and supply chains, and looking at social media trends to gauge reputational risks. However, there is very limited quantitative data available from which corporations can evaluate water risk; rather, most remain dependent on qualitative evaluations. Investors, meanwhile, are seeking to determine the proper quantitative and qualitative metrics to evaluate water risks for the companies in their portfolios, and there are emerging tools and algorithms being developed that 'scrape' data from the web to inform these types of investment decisions.

As for policymakers, new data and visualizations can clarify complicated water issues and drive policy decisions. At the same time, policies can also drive data disclosure.

Yet, generally speaking, existing water policies and regulations at the federal and state level are out of date and do not reflect the current state of data and information capabilities; they are not necessarily designed to handle technological innovation, new data streams, or changing conditions. Water policies, therefore, need to be designed or interpreted to be as flexible and responsive as possible, and regulatory agencies need to begin considering how they will handle—or make use of—new types of data, particularly crowd-sourced data.

KEY FINDINGS

Building on these described realities of the current water management landscape, this report summarizes the Aspen-Nicholas Water Forum discussions of May 2015 and homes in on priorities for the U.S. water sector.

1. The rise of big data and new measurement technologies can transform the way that water is managed in the coming decades.

Effectively managing a natural resource requires being able to measure that resource accurately, and the water sector has historically lacked a significant amount of data regarding water quantity (particularly for groundwater), water quality, water flows, etc. New types of data collection techniques and big data—from satellite hydrology to data exhaust from cell phones—are offering a game-changing opportunity to improve water measurement capabilities.

New tools coming to the fore that are providing unprecedented quantities of data include satellite hydrology that measures where water mass is being lost and gained worldwide, Google Earth Engine's aggregated Landsat data on global surface water, and remote sensing opportunities like "smart rivers" that use real-time sensor monitoring. As cheap sensors increasingly become available and are used across the water system, and as data collected by the public are integrated into water management, local and regional water management will be better equipped to face the current challenges in public and private sector water management.

2. However, water data must be synthesized more rapidly than government agencies' current pace of analysis.

The quantity and variety of data are increasing far faster than they are being synthesized or used, particularly by government agencies. While most users would like water data to be public and centralized, the trend is toward data being private and diffuse, largely because of the transformations in data collection technologies, such as smart phones and drones.

There is greater need for synthesis than collection (except in the case of groundwater, which continues to lack basic data). Data management, synthesis, and application are needed to better inform water management decisions. Water data are also getting ahead of policy, in that the quantity and various types of data, and the wide variety of collection platforms, has moved beyond what was envisioned when most policies—federal or state—were designed and implemented. Federal regulatory agencies should immediately develop plans and programs for how they will treat or make use of citizen science and crowd-sourced data. It is likely only a matter of time before such data are more voluminous than 'official' data on which agencies currently rely.

3. A national water data policy is needed that standardizes data integration and storage for more effective water management across sectors.

There is no clear agency or organization in the United States that has taken leadership, or been given the mandate, to provide coherence to water data. Experts have noted a lack of leadership within individual regulatory agencies and a lack of planning to manage and make use of emerging data types.

There is no such thing as free data. The more open access data are, the more effort required to make them usable and actionable, and thus the more constrained they are to specialists rather than the general public. Instead of centralized water data, things are moving in the opposite direction: more data are now privately generated and stored for specific purposes than are being collected and synthesized for general purposes. The increase in personal drones, cheap sensors, and data privacy concerns will increase this trend. People have typically relied on federal agencies such as the USGS or the National Weather Service to aggregate water data, but that is not necessarily happening with newer data sources. Agencies typically charged with data collection and synthesis have constrained budgets that are difficult to allocate toward long-term data collection or synthesis efforts (even satellite commitments), compared to new initiatives.

While a 'national water policy' may not be attainable, there could be, and should be, a 'national water data policy.' The federal government should provide leadership in the standardization of how to curate, store, and make use of new streams of data that have broad societal relevance. Ongoing efforts within the private sector and agencies (e.g., the Open Water Data Initiative) should be funded directly by some compilation of state and federal resources, rather than the current approach of predominantly volunteer development. This does not mean that a single agency would centralize water data; rather, an agency or agencies would develop the protocols and processes needed for how water data can be integrated and stored to maximize its utility across sectors and purposes to increase opportunities for public and private sector innovation, data sharing, and solution development.

4. Overcoming privacy constraints would help to maximize the potential of water data.

Issues of data privacy are critical to address, particularly for agriculture, the largest user of water and often far more sophisticated in technology than other water users. Because ever more data are being generated privately, these data have large potential to inform broader, regional water management decisions, but they could also be used against those actually generating the data. Tools and mechanisms for data sharing from private sources to minimize risk to data providers are needed.

Most public data (e.g., USGS soil maps) do not match the scale needed for contemporary and emerging high-precision agriculture, which is typically at the sub-field scale. The private sector has been rapidly developing new geospatial technologies, from remote sensing to in-situ sensors, that are transforming agriculture, potentially leading to a 'blue revolution' where comparable crop yields are produced with less water use. The greatest data and information gap in agriculture is about groundwater, particularly basic information regarding the size and yield of local aquifers.

There is significant need for agricultural water data to inform broader management, whether of environmental regulations or future land use planning. It will be possible in the future to measure agricultural water use using remote measurement without farmers' permission (e.g., satellite or drone-based imagery), but it would be far preferable to develop a mutually beneficial data-sharing system that allows farmers to retain control of information while also providing data to those heavily affected by agriculture, from downstream water users to investors.

5. Accurate assessments of private sector water risk require better matched data sources and data analytics across industry.

Publicly available data are typically poorly matched in terms of scale, location, or purpose to specifically evaluate the water-related risk of a particular water user. It is thus typically not possible to quantify water risk at the facility or utility level, let alone to analyze water risk at the company or portfolio level. Also, data provided by companies are often only qualitative. Quantitative evaluation of water risk by companies or investors will require a substantial increase in data provision by the water users themselves.

There is opportunity, and need, for data analytics around water use at the level of the firm relative to the stability and security of the water supply at the individual site level. Only when this type of data are made available can synthesized, company-level (or even portfolio-level) risk analysis be realistic.

THE WATER CONTEXT

Water crises related to water quantity or quality are presenting serious ongoing challenges in the United States and elsewhere. While the amount of water in the world stays the same, the amount of freshwater has been changing; as groundwater is pumped—whether for drinking, agriculture, energy, or manufacturing—and ice sheets and glaciers melt, freshwater is increasingly going into the oceans. Many places in the world also face quality issues such as nutrient runoff or pollutant contamination, along with contamination of significant groundwater resources.

The water cycle and water availability are in a time of flux due to forces like population growth and climate change. Some of the ways they are changing are predictable, enabling regions to plan for the changes and take action. However, some of these changes are more difficult to predict, requiring regions to be flexible and responsive. In most places, water shortages will not be solved on the supply side. Particularly in the United States, it is unlikely that there will be many big new dams or desalination plants lining the coasts. While there are still groundwater sources that are being tapped for the first time, the majority are being depleted more rapidly than they are recharged. Storage has been the traditional way that this sector has addressed supply problems, but there is only marginal opportunity for using storage to manage water supplies in comparison with the scale of water use.

While the amount of water in the world stays the same, the amount of freshwater has been changing.

Solutions to these water challenges will not come from a single sector alone—not government, not academia, and not the private sector—and are inherently local and regional, and also temporal. In the United States, there is a chasm between Eastern and Western states, with the West constantly challenged by water scarcity while the East is increasingly challenged by water quality. Within the West, there is significant regional variation, including stark differences between water challenges in the Colorado River basin and challenges in the Northern California water system. In Texas, urban water use is growing nine times faster than all other water uses combined, while in many places agricultural water use is the key driver of water problems. There is significant need for all sectors to improve local and systemic water management, particularly by using data-informed analytics that take advantage of newly available water data.

While there are still groundwater sources that are being tapped for the first time, the majority are being depleted more rapidly than they are recharged.

To address complex regional questions of water management in the coming decades, the water community has set out to assess the opportunity that big data presents for better management of our water systems. The following sections explore various aspects of water data and how they can transform modern water management and governance for long-term sustainability and resilience.

DEVELOPMENTS IN WATER DATA

Water management is entering the realm of "Big Data"—a phrase that is used to capture four broad information trends: volume (sheer quantity of data), velocity (speed at which data are being generated), variety (increasingly unstructured, unintentional data with little pre-defined structure), and veracity (questioning the trustworthiness of data as the world's digital footprint grows). The challenge is to create value from data in a reasonable time frame and in a way that increases the sustainability of water resources.

Management requires measurement. Data are thus fundamental to water management and water policy. Water data collection and analysis, however, are incomplete and rather disorganized. Understanding what data we have, how we collect it, and how to standardize and integrate it may well be a prerequisite to taking action to address a wide range of water challenges.

UNDERSTANDING BIG DATA

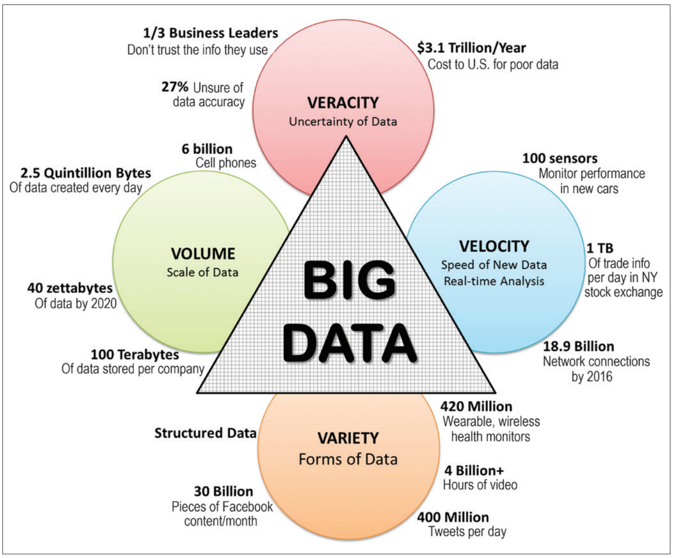

Figure 1 Components of big data with examples (From the Nicholas Institute for Environmental Policy Solutions, Duke University, 2015)

WATER DATA TODAY

Hydrology has been and remains in a curious, giant data gap. Water—the most basic aspect of life—often goes unmeasured. We are particularly ignorant of the quality of water and the quantity of groundwater, our largest source of freshwater. Without knowing accurately and precisely how much water we have, how much we use, or how that is changing over time, it is difficult to figure out how to allocate water among a range of competing needs or how to plan for the future, let alone how much to charge for water that is provided.

There are several reasons for our ignorance. For one thing, there is a lack of transparency around water data in almost every sector; there is typically a greater incentive to *not* share water data than to share it. Continuity of public data collection operations is also a challenge; maintenance and enhancement of monitoring infrastructure suffers in comparison to new initiatives in which federal or state politicians tend to have more interest, which harms long-term data gathering efforts.

There is a lack of transparency around water data in almost every sector; there is typically a greater incentive to *not* share water data than to share it.

In addition, there has been a lack of sensors and other data gathering tools; that is a solvable problem, as the technology exists for good bottom-up data gathering, but there are innumerable other issues competing for money, attention, and leadership. The data that get generated are often based on which proposals get funded, but the political will to fund those kinds of activities is generally lacking and has been declining in recent years.

At the state level too, if one looks at the data budgets for state agencies, one quickly realizes that such funding will not produce the data or the data-derived products desired or necessary. There is a need for leadership—for an external push by a community of relevant stakeholders (i.e., the data users) to advocate for data-gathering and synthesizing efforts and to highlight the critical needs they would satisfy.

NEW DATA TOOLS

Traditionally, researchers gathered water data sporadically at discrete locations and then inferred the status of broader areas from those data, such as measuring the depth of the Nile River for thousands of years, or the depth of the Mississippi River at New Orleans for hundreds of years. That kind of data collection still occurs, but there are also remarkable innovations happening in the ways we can collect water data, both remotely and on the ground.

Data acquisition has expanded dramatically in recent years; remote sensing technologies, along with the widespread adoption of geospatial analysis, have increased our capacity to observe and monitor water stores and fluxes over enormous spatial scales and extents. More recently, there has been dramatic expansion of in-situ technologies, from high-resolution water quality sensors to sensor networks that allow greater integration of available data. Increasing growth in the variety of data, particularly unstructured data that include web content, social content, and crowdsourcing, is dramatically changing the landscape of water data. For example, tweets may already be a greater source of flood-stage observations than U.S. Geological Survey stream gauges.

Remote Sensing: Satellite Hydrology, In-Situ Sensors and Drones

There has been dramatic expansion in remote sensing capabilities, ranging from federally funded satellite missions focused specifically on water measurements to private satellites controllable by individuals to the dramatic expansion in the availability and use of drones (automated unmanned vehicles). These capabilities provide data that are spatially expansive but that require significant data analytics to yield useful information.

Tweets may already be a greater source of flood-stage observations than U.S. Geological Survey stream gauges.

Water management is moving into a golden era of both satellite hydrology and simulations. In addition to gauging water mass (see box), satellites can also help us map every structure standing on the planet and understand where the people are—essentially creating maps of water demand, energy demand, infrastructure usage, and the like. We can then project forward about where people will be in decades to come, enabling us to plan for the future. In the United States, for example, the projections show a clear pattern of new growth occurring in the Western and Southeastern states, where there are already water scarcity challenges.

NASA'S GRAVITY RECOVERY CLIMATE EXPERIMENT (GRACE)

NASA's Gravity Recovery and Climate Experiment (GRACE) involves two satellites that can identify where we are gaining or losing water mass all over the world, providing unique insights into freshwater availability.

GRACE was used to generate maps showing cumulative groundwater loss in California from 2002 to 2014; the GRACE data (along with data from the U.S. Geological Survey) show that California's Central Valley has experienced small recoveries in the groundwater table during wet periods and huge declines during droughts, so the overall trend is strongly downward—like a tennis ball bouncing down a flight of stairs.

GRACE data have also been used to show how the upper half of the United States has been getting wetter since 2002 while the lower half has been getting dryer, how freshwater scarcity is prevalent in the big food-producing regions of the world, and how the world is losing water in ice sheets and alpine glaciers. The maps generated by GRACE data have the potential to not only increase dramatically the scale of groundwater data availability, but to also be powerful communications tools.

Big data such as these can help water utilities understand trends in land use and climate that will influence key decisions about planning an adaptive and responsive water system. Big data and modeling can also help water utilities and land use planners collaborate to assess what amount of water will be needed and is available for different city growth scenarios. New computing is allowing us to monitor and model these types of dynamics rapidly, which opens the door to near real-time simulations.

Like satellites, in-situ sensors have improved dramatically in their capacity to measure constituents in the field at near real-time resolution. This capacity is becoming available for monitoring and applications. Some of the most rapidly adopted technology developments have been for in-situ, real-time nutrient sensors. Emerging sensors allow measurements to be taken in the field, reducing the logistical efforts needed for each sample while dramatically increasing the amount of data that can be collected. The cost per data point has been reduced by orders of magnitude.

As these sensors have decreased in size and increased in precision, organizations like the USGS have been developing and deploying combined sensor packages that allow multiple real-time observations of water quality from sites. There is a growing network of these sensor observations positioned around the United States; substantial data are being developed from key rivers.

New sensor technologies are dramatically changing the type and resolution of data that we can collect as well as data collection approaches—but their cost can be high: one nutrient sensor, for example, costs around $15,000. (One federal agency is attempting to spur development of reliable nitrate and phosphate sensors costing $5,000 or less by promising to purchase them.) Another challenge is the storage and management of the vast quantities of data generated by the sensors.

Remote Sensing Opportunities

New data insights do not necessarily require new satellite programs. We have decades of Landsat data (at 30m resolution), but new tools such as Google's Earth Engine project have been taking the freely available Landsat data that have already been uploaded (much of the Landsat data are still stored in tape canisters in locations around the world) and making them more accessible to users for manipulation and analysis. Such tools can be used to better understand water issues, such as by producing a global surface water map showing where water is always, sometimes, and never present. A key aspect of this type of effort is that it is taking some of the remote sensing water data and putting it into a format that is far more usable by diverse audiences, rather than being solely in the realm of private data and specialized software. It is also important to remember that not all remote sensing is by satellite; there are airborne remote sensors and drones as well, which are increasingly common and generate a rapidly growing quantity of data.

Organizations can use remote sensing and GIS modeling in some areas to identify hotspots for restoration and places to direct funding and outreach at the parcel scale. High resolution land cover data (at a 1m scale instead of a 30m scale) bring the ability to do a range of other analyses, such as identifying impervious surface cover and understanding the potential influence of specific fields on downstream reservoirs or estuaries. Concentrated flow path mapping (using LiDAR) can tell you where and how much water is moving over the landscape, enabling calculation of pollution flows and identification of locations (including upper watershed areas) for best management practices at a field scale; we are not that far away from being able to sync flow data to water quality data in order to show in real time what is happening during base flow, what is happening during storms, and where nutrient loads are coming from and going. Transparent data can also help validate best management practices and illuminate whether they are working or not.

It is not out of the realm of possibility for water quality sensors to be part of a smart phone platform in a matter of years.

Remote sensing can produce a tremendous amount of data, but it is most useful when validated with ground data, and there are significant developments there as well. Technologies are already enabling on-the-ground data gathering to support real-time management decisions, such as "smart rivers" that have real-time sensor monitoring. In Lake Erie, there are now buoys (funded by the federal government via the Great Lakes Initiative) that monitor in real time a wide range of water quality parameters and physical parameters, the data about which is fed into a model (as is satellite data) to forecast when algal or other events will occur so that treatment technologies can be adapted accordingly. Being able to forecast such events remains a challenge, but the information infrastructure is being put in place to make such forecasts a reality.

There are numerous efforts to further accelerate technologies that can support better water data gathering. Government agencies, for instance, are sponsoring challenges to develop and deploy low-cost nutrient sensors. We may be on the cusp of making huge progress at the $5000 price point for regulatory-quality nutrient sensors and at the $50 price point for sensors for citizen science. Cheap sensors could be a tremendous boon in several ways. For instance, they could markedly improve and reduce the transaction costs of nutrient trading; verification is critical to trading (which is why thus far most of the trading has been between point sources), and the low-cost ability to measure nutrients from non-point sources will be transformative (*see box*). It is not out of the realm of possibility for water quality sensors to be part of a smart phone platform in a matter of years.

THE WATER MARKET APPROACH

With the development of sensors and real-time monitoring and reporting, it is reasonable to expect that water quality trading programs can manage their trades in a way that ensures actual offsets of the unit of interest; for instance, the programs could show through actual measurement rather than through conversion factors that a unit of nitrogen loading has been removed. This evidence-based policy approach would increase the credibility of the market system and could increase participants.

One of the most critical limitations of water quality markets to date is that they require no actual water quality measurement as part of the trading process, leading to uncertainty and limiting the role that the market can play. Best Management Practices (BMPs) are a surrogate for actual reductions in nonpoint sources of nutrients or actual measured reductions in temperature. Conversion factors are applied to convert area of BMPs to units of nutrients or thermal change. Even the well-known Tualatin River thermal trading program requires temperature to be measured only at the watershed scale, rather than in proximity to the BMPs. This approach is reasonable only if water quality data are difficult and expensive to collect.

While water quality markets are in their infancy, water quantity markets have been in existence for some time. The system of property rights in the western United States, which allows separating water from land, has facilitated markets. In California, there are more than 14,000 statements of diversion, some of which go back to pre-1914, when the state officially established its permitting process. Water trades are gaining in value, especially in locations experiencing prolonged draught; in 2013, California saw a 180% increase in total dollars and a 220% increase in total volume of water traded over the previous year due to the multi-year drought. A key to the success and expansion of water quantity markets is use of technology to account for water in the system.

CITIZEN SCIENCE

Over the past decade, advances in Internet availability, GIS-enabled web applications, and online data entry systems, along with the ubiquity of smart phones, have made it possible for citizens to engage with and contribute to the scientific process, as well as generate data, on an unprecedented scale. Citizen science is the open collaboration of members of the public and professional scientists, primarily for the collection and analysis of data. Crowdsourcing is a process of voluntary contribution from the public, or a group of trusted individuals or experts, typically through the Internet.

Through citizen science and crowdsourcing, scientists and water managers can access greater amounts of quality data at substantially less cost. The democratization of science research, in turn, empowers communities to engage with resource management decisions. There is growing investment in the investigation of appropriate use of such data and in further engagement of the broader public in citizen science—for example, the Federal Community of Practice for Crowdsourcing and Citizen Science, a network of 100-plus employees from more than 20 federal agencies.

With more low-cost water quality monitoring will come a wave of variable-quality but potentially very useful data from citizen scientists. The distinction between community-gathered or citizen science data and data gathered from some 'authoritative' source should not be overstated. Both kinds of data have errors associated with them. All datasets have errors. Data just need to be handled in the appropriate way to generate useful derived products. The challenge is figuring out when and whether the collector of the data affects the veracity of the data.

Through citizen science and crowdsourcing, scientists and water managers can access greater amounts of quality data at substantially less cost.

Understanding the Role of Citizen-Collected Data

There are several crowd-sourced data websites in other fields, ranging from the location of potholes to whether people felt earthquakes. Crowd-sourcing data efforts such as police tip lines and amber alerts have also proven very successful. These efforts produce very noisy data, but data that, when compiled over numerous (i.e., thousands) of observations, can provide as much (or more) information as formally collected, precise data. Crowd-sourced hydrology, even on something as simple as water levels, could produce some erroneous data, and it also could involve very sporadic snapshots of particular locations, but not all purposes require highly precise data.

While crowd-sourced data currently cannot be used for regulatory purposes (which require a predetermined level of accuracy and precision, along with standardized methodologies), less precise data are certainly suitable for something like getting a general sense of problem areas. The acceptability of citizen science and crowd-sourced data depends on what one wants to do with the data. To be useful, though, some kind of platform must exist to receive the citizen data and convert it into meaningful information.

The organizations that are trying to do some of the actual on-the-ground work (e.g., sampling water) may not have the capacity or expertise needed to use the range of big data tools and models to their full advantage. There is a need for big data researchers to better interface with the citizen scientists and small organizations that are doing the actual monitoring. Perhaps most importantly, there is a desperate need to understand the veracity of crowd-sourced and citizen science data through direct comparisons with traditionally collected data, particularly in the potential realm of regulatory applications.

Research programs are needed that can help understand what types of water data are most amenable to crowd sourced collection, what types can be approximated using surrogate observations (e.g., using color of water rather than actual solute measurement), and what types of data (or decisions) should only be based on formal data collection. It should also be recognized that such typology of water data will not be static, but rather will change dramatically as technologies change. This is a realm that would greatly benefit from basic natural-social science research funding.

CITIZEN SCIENCE PROGRAMS ON THE GROUND

The **Meteorological Phenomena Identification Near the Ground** (mPING) mobile app from the National Oceanic and Atmospheric Administration (NOAA) has developed publicly available crowd-sourced weather reports. So far, more than 600,000 ground-based observations have been used to help verify weather models. Reports are immediately archived into a database at the National Severe Storms Laboratory (NSSL) and visualized on a map.

GLOBE, a NASA-sponsored network of students, teachers, scientists, and citizens, has partnerships with NASA satellite missions pertaining to water: SMAP, GPM, and CloudSat. Volunteers—primarily teachers and students—help verify satellite measurements to crowdsource water efforts.

The Community Collaborative Rain, Hail and Snow Network (CoCoRaHS), based at Colorado State University, uses a citizen science group to monitor precipitation and snow. This program has grown to include a network of some 33,000 volunteers collecting data, and CoCoRaHS data are helping emergency managers, city utilities (water supply, water conservation, stormwater), insurance adjusters, the USDA, engineers, mosquito control, ranchers and farmers, outdoor and recreation interests, teachers, students, and neighbors in the community.

Public Lab is a crowdsourcing nonprofit focused on developing open source monitoring devices and software for collecting air, water, and land data. For water monitoring, the lab makes low-cost sensors (<$100) for the general public to deploy to measure temperature, conductance, and water depth.

Many citizen science efforts complement broader scientific data collection efforts, and several of these are being used to increase the accuracy and precision of weather and climate measurements, which are often otherwise limited to remote sensing and a few on-the-ground weather stations (see box). Citizen science programs rely on relatively easy-to-make observations by the public to supplement data collection by scientists using more formal approaches. These programs may increase the sophistication of collected data while simultaneously simplifying the data collection. One of the key aspects of citizen science groups is that they can dramatically increase the amount of data that is collected, and in some cases, they can provide enormous amounts of data in difficult-to-reach places.

DATA ABOUT THE PUBLIC

People can be not only gatherers of water data but also producers of it. Better measurement of actual household water use (even anonymized) can help achieve better outcomes in bending the demand curve downward. Innovation in the metering and tracking of efficiency in water use in the home, however, lags far behind the energy field, in part because water is very cheap and is expected to be so. Until water prices go up and utility revenues are decoupled to some degree from volume, innovation will have a limited value proposition.

Nevertheless, there are very intensive data research trials underway on how people use electricity and water, including anonymized end-use appliance-level data collected by meters at one-minute intervals. Getting data from the home can be done in different ways, each with pros and cons. The traditional way is sending a meter reader every 30 days, with the customer getting a monthly bill, a statement that is not particularly useful nor informative. Advanced metering infrastructure (AMI) has the utility collecting data automatically and a third-party company converting the data to actionable information for the customer; this approach can gather data at scale but assumes that utility data centers have the interest and capability to do data cleaning and management at the velocity required. Another way is to use an in-home hub, which gathers the same signal as an AMI-type system and routes it to a data center; while this approach relies on individual adoption instead of utility deployment, it allows for better control over data quality and analytics.

Better measurement of actual household water use (even anonymized) can help achieve better outcomes in bending the demand curve downward.

Water utilities are most often relatively small, in contrast to electric utilities, and generally do not have the funding or scale for data-centered investments like AMI deployment. (As conservation efforts increase, utilities are experiencing less consumption and are therefore seeing revenue destruction, which means they are getting even poorer.) Only the largest water utilities serving major cities (e.g., Philadelphia, Denver) have anything close to the IT systems needed to support large-scale data management. Many utilities do not even have email addresses for most of their customers. In addition, utilities are focused on providing a safe, reliable, and cost-effective water system and generally have to be conservative about the ways they evolve; they tend to be risk-averse, adopt technology slowly, and prefer to have others be the first-movers. Similar to other water users, utilities also have concerns about data and user privacy.

Water utilities therefore are not usually going to be innovators for data operations; that will be better done by a third-party provider used to managing a lot of data from many distributed points and converting it into actionable information. Exploration of data partnerships like those in the electricity sector, where utilities and third-party providers partner to provide services and information to customers, is just beginning in the water sector.

People tend to be much more comfortable sharing data with the cloud or with peers than with a centralized authority.

In general, the value propositions for water utilities need to be much richer to get utilities to form partnerships and make incremental investments in data-related technologies. There are many possibilities. Utilities could use AMI to find meters they did not know they had, that are not operating, or that are not in the billing system. Similarly, technology improvements allow for some continuous monitoring of customers over time, which can provide tremendous value, including potentially allowing utilities to build less redundancy into the water supply system by cutting demand at particular times (e.g., by adjusting rates).

Another potential source of untapped data is data exhaust, or the data generated by digital activity—the digitally trackable actions, choices, and preferences that people generate as they use digital devices. Data exhaust is used for market research and to target advertisements on the basis of users' online preferences, words in emails, or Internet searches. A study of data exhaust showed that two weeks' worth of location data on an individual, combined with location data from the person's two most-sharing friends, was enough to place that person within a 100-meter radius with 77% accuracy. Data exhaust may be an untapped source for water. Very simply, it could be used as an early indicator of water main breaks. It might even be used to track the location and timing of homeowners' applications of lawn fertilizers and pesticides, which wash into nearby streams.

The cloud also offers significant opportunities to gather and analyze data and to achieve economies of scale in the water sector. People tend to be much more comfortable sharing data with the cloud or with peers than with a centralized authority, whether the government or utilities, which could enable peer-to-peer benchmarking and water shaming. For utilities, new players are arriving that can aggregate information, create linkages among utilities, bring in and share best practices, and provide a bridge between innovation and tradition through application of cloud-based data storage and cloud-based analysis. There are big disincentives to consolidating physical infrastructure in the water sector, but it should be possible to connect back offices, enabling aggregation and combination of data in ways that can be incredibly valuable.

INCENTIVES TO PROVIDE DATA

While the public may produce a great deal of water data, many people and entities have little interest in sharing it. Water utilities generally will not share it either. Incentives for voluntary sharing of data must therefore be put in place.

One approach could be purely economic. If water utilities enable users to give (or sell) their data to third parties of users' choice in order to provide services, as is starting to happen more in the electricity sector, there would be an economic incentive for data sharing. Similarly, farmers may find that water use data can be sold to a variety of interested parties, such as companies interested in demonstrating the water-efficiency of their products (e.g., seeds, equipment) or nearby water utilities that are part of the same watershed and thus connected hydrologically.

Water users are unlikely to offer their data if it will be used by governments to initiate enforcement actions against them.

Provision of a valuable co-benefit could be another approach. For example, customers may be more likely to adopt in-home gateways that provide water use data if the devices also provided leak detection. Water leaks can cause significant damage to a structure, giving customers (and home insurers) a strong incentive to get data devices with leak detection abilities into homes. Farmers might similarly share data if doing so would make farming easier; working with farmers to help them reduce costs and grow more crops, along the lines of the old Agricultural Extension Service, can help make more water data available. In the Ohio River Valley, those seeking to participate in the emerging water quality trading market (to limit nitrogen and phosphorous loads) had to agree up front to do a certain amount of measuring and data disclosure in order to get the greater flexibility in meeting compliance requirements.

In contrast, water users are unlikely to offer their data if it will be used by governments to initiate enforcement actions against them, or by the media to vilify them. Aggregating data such that individual users cannot be identified and punished (whether by government or the media) can help unlock flows of data, and better data may provide greater understanding about voluntary or behavioral modification pathways to achieve the same end. Why one wants to get data influences how those data are gathered and how that data-gathering effort is received.

MAKING DATA ACTIONABLE

One can think of data as being of different types or sizes, ranging from big data (i.e., too much for a single machine to handle) to small data (i.e., humans could make a decision based on it). There is also a clear progression from data to information to knowledge to decision-making. Data per se are not enough; data need to be made actionable.

There is an inextricable and necessary linkage between data and the context for which it is being used – and there are many potentially valuable uses. Big data have the potential to create revolutions and disruptions. Early on, its applications will likely be incremental improvements to existing processes, but the moonshots could be a few years further down the road.

Big data and the analyses and visualizations that can be done with them can help to make a compelling case about the nature of water problems and the need for serious action. Most people have virtually no data on their water. They only get their bill (which they do not even see if they have automatic payments set up), and that bill is ugly, comes long after the water usage has actually occurred, and tells them only how much water they used (without context and often in units they do not understand). They usually have no idea where their drinking water comes from, and they have no idea what a water quality report is. Data creates an opportunity to change the way the world looks at water – if it is turned into understandable, actionable information that can help make end users partners in water efforts. We are still a long way, however, from having the visualizations, communications, and consistent messaging needed to get water data in front of the general public in a way that can change behavior and shape the public dialogue.

There is a clear progression from data to information to knowledge to decision-making. Data per se are not enough; data need to be made actionable.

We may need to talk less about data and more about tools. Data will not accomplish anything on their own. The key is to turn big data into small data and into information products that are useful. It is the D part of R&D—beyond research, more development is needed to create tools applied to answering specific questions. Developers and researchers could start by figuring out what tools people want so that they can make better decisions, then work backwards to figure out what data should be collected to create those tools. The answer is not always new data; a lot of data exist to answer some of the more basic questions. To make progress on a rapid timescale, public-private partnerships will be essential. Some agencies are already making their data public and asking private companies to provide a useful commercial service with it.

The rules are different for the public and private sectors when it comes to making data actionable. The National Weather Service, for instance, is prohibited from posting any kind of derived products, which means the public has to turn to the private sector for such products. It can be a fine line, though, between providing data and providing products. Some data are observed, while some things are derived. For instance, we measure water levels, but stream flow data is derived. Similarly, the GRACE satellites do not directly measure groundwater depletion; maps showing such depletion are a derived product. Scientific insight is important not just in gathering the data but in accurately analyzing it to help inform decisions.

Data creates an opportunity to change the way the world looks at water – if it is turned into understandable, actionable information that can help make end users partners in water efforts.

There are other challenges in making big data actionable, such as mismatches between data needs and availability. For instance, climate scientists have the highest levels of confidence in mapping data at 4 km resolution, whereas city planners need resolution closer to 1 km. More broadly, the type or scale of data needed by people in water management or who directly use water (e.g., agriculture) appears in some cases to be fundamentally different from the data generated by big data projects. If different data are needed for different users for different outcomes, there may need to be a wide variety of products, solutions, and applications. Conversations between data providers and the sectors that will apply the data need to continue in order to help data providers understand the different types of data uses and needs that exist.

In addition, to truly be actionable, data have to be put together to tell a coherent story and to provide meaningful context. As important as data are, there is a need to make the case about how water and the various issues surrounding it affect people, communities, and economic sectors. More visioning and scenario planning could provide helpful stories for those not immersed in water resource management, helping people to understand the social justice, environmental, and other implications of the water resources status quo and of what happens as populations and demand grow.

DATA STANDARDIZATION AND INTEGRATION

Standardizing Water Data

There is a general sense that data are getting ahead of us, and even as more are being generated, we are not necessarily able to use the data that already exist. We are drowning in data but lacking in intelligence. This is not unsolvable; the key seems to be harnessing, standardizing, and integrating the data.

Much of our existing data are only just beginning to be aggregated and organized. For instance, publicly available data from tens of thousands of U.S. water and wastewater facilities are being aggregated and transformed into predictive market analytics for the water sector, so that companies developing equipment and technology for water infrastructure can identify the utilities and cities that might need their technologies. Those data are currently in thousands of filings in thousands of places in thousands of formats, but by centralizing and normalizing them, deeper visibility into the market can be created.

We are drowning in data but lacking in intelligence.

Similarly, some states are starting to roll up all their local water data and are using tools to visualize them statewide in order to better understand any projected gaps between supply and demand, determine what behavioral or technological interventions across sectors could close those gaps, evaluate the costs and benefits of those interventions, assess the impacts of various scenarios, and inform public policy.

Such aggregation requires standardization. There is no common data standard in the water sector, unlike many other sectors. Just as there is a clear data format for stock market information, a lot of water information could be standardized to be consistent in structure and format. Creation of standards for collecting and reporting water data are important to help define what will make a scalable, secure platform, what the access controls are, and how third parties will be incentivized to put in data from a range of research and commercial sources. Standardized approaches and tools for data generation and collection will also make it easier and cheaper for cities and utilities to generate data and transform it into information.

CONSORTIUM OF UNIVERSITIES FOR THE ADVANCEMENT OF HYDROLOGIC SCIENCE, INC. (CUAHSI)

The water data community is attempting to streamline data sharing through interoperable web services using a standardized information model formalized in XML (WaterML 2.0) to transmit hydrologic data. One open and free water repository is the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). CUAHSI has developed information models, data standards, and semantics to structure data for retrieval for integrated analysis by multiple users, and it has begun the process of standardizing data management approaches. CUAHSI is funded through a grant from NSF to develop infrastructure and services for the advancement of water science in the United States.

The increasing variety and volume of data relevant to water management make single-agency curation impractical. If multiple organizations are to curate and manage such data, some type of standard operating procedures will be needed to govern the data production process to ensure that the data are of a consistent, known quality and will meet their intended purpose. Examples include USGS data collection techniques and methods and the International Organization for Standards (ISO) standards for inter-comparability of data.

One of the often-overlooked roles that resource and regulatory agencies have played in data curation is creating a community-wide standard of practice for data quality, precision, and accuracy. Indeed, federal agencies, such as the USGS and the EPA, have historically been careful to ensure the precision and accuracy of their data prior to publication, in no small part because of the critical economic and safety role that these data have played (e.g., in developing the Colorado River Compact, monitoring flood-stage elevations on large rivers, and working with the Federal Emergency Management Agency or FEMA). As data sources outside agencies become available, questions arise about which agencies should be tasked with curation of toxicological data, which with stream gauge data, and so on.

Publication of data raises other questions. Historically, such publication has occurred on an annual basis, although provisional data have been made available more rapidly. Today, there is increased focus and reliance on real-time, continuous publication of unit value data, requiring great thought about how to use interoperable data structures.

Next Steps on Data Aggregation

As a first step, we need to define a minimum data collection and reporting framework—what is being measured, by whom, where, why, and when. We need to define the foundational dataset on issues such as temperature, salinity, nutrients, flow rates, and quantity, with a certain level of spatial and temporal density. Weather forecasting could provide an apt analogy; if there was not a standard government-driven foundation of data, there would not be decent weather forecasts.

Similarly, there is a need to better define a baseline set of water standards, indicators, and measurements, where the private and public sectors use the same underlying body of data collected by the public sector (augmented by the private sector), relying on both ground-based and remote sensing to gather the core data on the state of our water system. Perhaps a federal role could be to work with the states to define and set the standards for that foundational set of data and to drive local data collection—or perhaps a group like the Aspen-Nicholas Water Forum attendees or some other partnership or consortium could be the ones to identify what should be in a standardized baseline framework.

The U.S. Geological Survey already has a research program called the National Water Census that aims to provide all elements of the water budget at a 30 square mile scale, and stakeholders may want to dive into that effort, accelerate the process, and make sure it helps us understand how much water we have, how much we need and use (including environmental uses), what data we already have that we can apply, and what other data we need at minimum.

Coming up with a standard framework and with data standards will not be easy, but it should be achievable—and could be accomplished in the relatively near term. There is also a need for standardization of communications protocols. Currently, devices use proprietary communications protocols, limiting interoperability. It may take the entrance of new big players (e.g., major telecom companies) to force some level of homogenization of data and communications in the water sector.

Integrating across Data Types

Data standardization enables integration of data collected for different purposes. As more data come online, it becomes increasingly challenging to organize and integrate them with existing datasets. Satellite data at a large scale, scientifically-collected data at a smaller scale, data collected for local water management, data collected for special purposes, and many other data streams need to be integrated in some way to help inform the conversation. Some data types could be more challenging than others to integrate. For example, there is a question as to whether there is a place for integrating manual observations of water as we increasingly desire instantaneous information. End-use water consumption data are another significant data piece that has to be more fully integrated into a master dataset (not just owned by each utility).

As more data come online, it becomes increasingly challenging to organize and integrate them with existing datasets.

Social science data can be particularly challenging to integrate. Some social data (e.g., social media data) can be integrated pretty easily into data platforms, but traditional social science methods in the natural resources and agricultural worlds produce data of a very different type. Such data may be more complementary than able to be integrated. Such data can provide context on the social construction of water (e.g., what it means to people, what they value about it), can provide essential framing as we move to integrate data into the world of policy recommendations, and can illuminate equity and justice issues at the local scale. There is a role for qualitative data—repeatedly asking questions, looking at words instead of numbers. Perhaps water preference questions could be added to the suite of existing social science data gathering programs that ask people about their preferences on a range of other issues. Actually talking to people and asking them questions can be much slower than a satellite passing overhead and lacks the volume and velocity to be integrated into big data efforts, but it complements such efforts.

Lack of data integration remains a barrier to transforming the way we use and manage water. Data integration faces three major barriers. The first is intellectual and resource capital. The water science community is typically based in the natural sciences and engineering rather than computer sciences and engineering. The community's skill set does not include big data generation, curation, and publication. Many local water management agencies and utilities have neither data scientists/managers nor the resources to hire these professionals. The water science community needs to develop its work force to fill this emerging gap in water data management.

Another key barrier is the lack of incentive for utilities, industries, and local governments to increase the availability of their water data. Releasing data entails a lot of work: addressing data privacy issues, controlling the quality of and standardizing data, and maintaining a website. Nevertheless, industry may be spurred to provide data by the development of institutions such as CDP that seek the disclosure of environmental information by businesses.

A third barrier is lack of clarity about what entity is responsible for integrating data across agencies, scales, and platforms. Data intended or expected for one purpose can often be quite valuable for completely different applications. Current management of water data does not reflect the end use of much of those data.

DATA INTEGRATION INITIATIVES

The **Open Water Data Initiative** involves several federal agencies and stakeholders focused on organizing the nation's water data and harmonizing data protocols and practices. The aim is to move water data from a catalog (i.e., a big list) to a service and from there to enhanced products and applications (which will be where the public and private sectors need to work together). The Initiative is focusing on particular use cases—selecting problems (e.g., floods, droughts, spills) and figuring out how to solve them using open data—to begin to organize data and to ensure that there will be useful, practical outcomes. Funding for the Initiative is currently pending in Congress (though agencies are starting to work without funding).

IBM's partnership with Sonoma County Water Agency (SCWA) uses an integrative data-centered approach to water management by reducing water stress felt by the northern California region's 600,000 individual users, including many wineries. Using new data streams and analytics, IBM generated "geographical and system map views" of SCWA's water management system and modernized SCWA's operating practices and infrastructure. The resulting systems allowed retail water providers to monitor the local Russian River and associated water transmission system in near real time. Data were derived from SCWA, local water retailers, upgraded water meters, USGS, and NWS. Sensors helped pinpoint defective meters, facilitating preventative maintenance and management practices for SCWA infrastructure. Additionally, SCWA's upgraded monitoring and management systems better informed its actions with regard to endangered populations of salmon and steelhead in the Russian River's ecosystem.

Pecan Street is a nonprofit organization, based at the University of Texas at Austin, aiming to provide users with a tool for gathering and analyzing real-time water and energy consumer behavior data from neighborhoods of homes equipped with smart sensors and the latest efficient technologies. It operates the nation's most data-intensive field trials on water and energy consumer behavior, and its volunteer research network has grown to more than 1,200 individual residences in Texas, Colorado, and California employing smart water meter data, smart natural gas meter data, and circuit-level (disaggregated) whole-home electricity use data, as well as smart phone monitoring technologies. Pecan Street gives utilities, technology companies, and university researchers access to consumer behavior, testing, technology verification, and commercialization services.

AGRICULTURE

Farmers are one of the most important audiences for water data and data tools. Given that water issues are so localized, both urban and agricultural water usage matter – and the two uses often draw water from different sources. In many parts of the country, such as Texas, urban water use is growing rapidly while the water supply is relatively static, and urban lawn care alone uses a huge amount of water. Of the water actually used in the United States, though, 80% is for agricultural purposes—more than 90% in many western states. Globally, the figure is 70%. Clearly, when dealing with water issues, there must be a strong focus on agriculture. As agriculture continues to rely on irrigation for production, the role of data has increased dramatically.

THE MISSING DATA IN AGRICULTURE

Farmers are one of the most important audiences for water data and data tools.

Unlike with electricity, where supply and demand are identical at all times, the water system relies on shock absorbers, in the form of reservoirs and aquifers. In dry years, when there is not enough water in the reservoirs for use by farmers, the aquifers get overdrawn as a source for agricultural water. Companies in California that switched to thirsty permanent crops now have to drill as deep as possible to preserve their investment; they are financially committed to the crop, and the aquifers are the only hydrologic mechanism for sustaining their investment.

In California and many other agricultural regions, we are living beyond our means with regard to the water budget. 'Safe yield' is a critical issue, but there are few accurate assessments of what safe yield is: we have surprisingly limited data on the amount of water in aquifers. (Similarly, in most areas, we have sparse or no data on water quality, apart from salinity.) At the same time, particularly given climate change, it is possible that the concept of safe yield is anachronistic, as water supply will become only more variable. Finding a way to do real-time groundwater monitoring to enable adaptive management of water may be needed. Indeed, there is a growing need for basic groundwater data.

PRECISION TECHNOLOGIES TRANSFORMING AGRICULTURE

Big Data-powered agricultural technologies (coined "precision agriculture" or "precision farming") primarily monitor hydrologic and meteorological variables—such as soil moisture, precipitation events, and snowpack levels—to better inform agricultural practices. Integration of big data technologies and agricultural practices holds substantial promise. The expansion of monitoring efforts will almost certainly yield more efficient and contextually appropriate management actions. As access to agricultural information becomes increasingly comprehensive and available, growers can better calibrate levels of input—that is, fertilizer, water, and land. By monitoring and collecting input and output variables, growers and suppliers alike can more accurately communicate performance and crop value, thereby solidifying beneficial linkages between producer and consumer.

There are lots of new players entering the intersection of agriculture and data, offering services and information about improving yields, how much water to put on a field, and the like. As with other aspects of water data, good data in farming is data that can be easily manipulated into actionable information that enables thoughtful analysis and better decisions.

Evolving precision agriculture devices such as yield monitors, smart machines (i.e., interconnected or automated farming equipment), and on-farm sensors operate on individual farms to generate data. But these data are only truly useful if they are compiled for analytics. This is the role of big-data warehouses, which store and redistribute data as well as serve as hubs for modeling technologies. Third-party Agricultural Technology Providers (ATPs) utilize this collected data to develop ag-retailer software or modeling tools for individual farm operations.

Good data can help solve the issue of flood irrigation. The amount of water in the soil a given plant can actually use (Plant Available Water, or PAW) can vary by up to 100% across a field. Most farmers are currently over-applying water on 90% to 95% of their fields to ensure that they adequately irrigate the limiting 5%. The same approach is used for fertilizer application. This results in excess runoff, loss of nutrients, and costs to both the growers and the environment. Every field, and every part of a field, has a unique amount of water it can use and particular nutrient requirements.

Data such as PAW data are needed at field scale that helps growers decide how much water to use where; such data needs to be collected at field scale, not just be landscape scale data that happens to cover someone's land. There is a need to reconcile the big-picture remote sensing data and the field-level data needs. They may well be two distinct data worlds, but big data resolution will get smaller and the software will get better over time. There is a gap with regard to tools that put data and knowledge in the hands of farmers and others actually using water, although this gap is being somewhat filled by innovative private sector technology companies.

New technologies focused on high-resolution geospatial mapping of soils at the sub-field scale, when used in combination with precision-agriculture, can enable growers to utilize PAW maps to precisely irrigate and fertilize the exact amount of water at the particular part of the field at the right time. Some leading practitioners are doing irrigation experiments in partnership with technology/data companies, making extensive use of high resolution ground-based sensors and Landsat imagery to micro-irrigate in small parcels to figure out how to create even greater water efficiency—increasing yield, reducing water use, and improving nutrient applications. The gains that can be made for both water conservation and nonpoint source pollution control are substantial. Importantly, this technology started with basic USDA soil maps but is now being dramatically improved through private sector geospatial and technological development.

Adoption of big-data technologies by the individual actors within the agricultural industry remains inconsistent.

Adoption of big-data technologies by the individual actors within the agricultural industry remains inconsistent. A 2014 *Harvard Business Review* report identified five major phases in the digital transformation of row-crop agriculture from the traditional mechanized farming system to multiple systems interlinked by big data and big data analytics to optimize performance. The most advanced farms in the U.S. agricultural industry are considered to be entering the fourth phase, wherein farming machinery sensors (e.g., planting, cultivation, fertilizer, and harvesting) are fully connected and functioning as an integrated system. The final phase is integration of various databases into farm operation decision making. Components of this fifth phase—a "system of systems"—include remote sensors, machine/human networks, farm accounting and finance systems, automated algorithms for agricultural variable analysis, and integrated communication systems.

A similar analysis acknowledges that the agricultural industry is rapidly approaching an inflection point with regard to the role played by big data. Between 2019 and 2023, big-data technologies will become synonymous with the agricultural industry.

There are substantial changes occurring in agriculture, and the private sector is investing heavily in big data for this space. New varieties of crops combined with new precision agriculture techniques that leverage high precision geospatial, real-timing mapping are creating the conditions for a new 'blue revolution' in agriculture. In the same way that the green revolution increased crop productivity using smaller amounts of land, the coming decades will likely see increased crop productivity using smaller amounts of water.

THE BROADER CONTEXT FOR FARMERS

Generating and collecting additional agriculture-related water data provides many benefits to farmers, but that activity does not occur in a contextual vacuum. There are substantial economic, regulatory, legal, political, and social obstacles to overcome in farming.

Because of the peculiarities of Western water law, for example, the default rule for many farmers in Western states is that they lose water rights when they save water (or they have to pay for it even if they do not use it). Under such policies, there is no benefit to farmers from saving water and no reason to accurately track water usage. If farmers could sell or lease saved water, that would create incentives for them to actually save water and conduct the measurement and data gathering needed to know what was used, saved, and sold (assuming they did not use the saved water to irrigate additional acres).

If farmers could sell or lease saved water, that would create incentives for them to actually save water and conduct the measurement and data gathering needed.

Many farmers collect at least some of the data they need—and would like more data from others at a useful resolution—but they often have policy and other reasons for not sharing it. One of the biggest challenges in managing water quality in several areas has been an inability to get data from farmers to show whether best management practices are working. One reason is that the Farm Bill contains rules about data confidentiality. Another is that there is a high degree of distrust between the farmers producing data and those entities (e.g., regulatory agencies) that want the data to monitor their behavior. In the past, when farmers have made those data available, they have been used against them. Little will change until that distrust is resolved.

Data can only go so far. There are other areas, such as climate change, where there is a lot of data but inadequate progress—because we have to deal with existing incentive structures and larger contexts. Water problems that have gotten solved thus far have often required difficult negotiations at a regional or local level, and a key to success has been building a common understanding of the problem. Data has a role to play in that, but the negotiations and common understanding are key. Those are difficult to achieve when it comes to agricultural water use. Farmers are often of the view that agencies are hostile to them and that cities will do whatever it takes to acquire the water they need at the lowest cost—and that farmers' interests will be sacrificed or at least reduced as a result. Until there can be real conversations among people about the division of water without particular groups feeling vilified, the water problems will remain unsolved regardless of how much data we have.

Data Privacy

A key concern as water data are collected and used more intensively in agricultural (and urban) applications is privacy. Issues around data ownership and the role of third-party organizations may hinder a complete integration of big-data technologies into the agricultural industry. As companies such as Monsanto, John Deere, and DuPont Pioneer roll out "prescriptive production" programs based on crowd-sourced big data, farmers/growers are presented with a troubling dilemma. On the one hand, these programs stand to potentially increase crop yields by upward of 25%; on the other, the programs may undermine agricultural competition and unfairly favor large-farm operations.

The American Farm Bureau Federation was among the first of many agricultural organizations to recognize these pitfalls, and it strongly advised its members to exercise caution when enrolling in data-sharing programs. In November 2014, big data service providers (i.e., ATPs) and a coalition of agricultural organizations met to discuss the implications of big data and guidelines for future operation. The two groups agreed to operate at a level of extreme transparency, awarding the bulk of data ownership to farmers. Consequently, farmers have the right to terminate data agreements at practically any time and must be notified if ATPs plan to share non-anonymized data. However, this agreement between ATPs and the agricultural coalition is based purely on principle, critically lacking the regulatory teeth to prevent future conflicts over data ownership and use. An applicable framework for managing agricultural big-data privacy issues might be found in a recent White House report regarding big-data technologies and online advertising.

Another key component for increasing the flow-through of data from farmers to the broader community is the data being provided by farmers to associations (e.g., almond grower or soybean grower associations). These associations are often able to compile and synthesize data from many farmers in an area and thus provide a degree of anonymization. Moreover, these associations are advocates for the agricultural industry in general and thus are supportive of the farmers' perspectives. Research groups and environmental management agencies should consider working with these associations as an initial step in assessing the types of data farmers need, what scale of analysis is useful to farmers, and what types or forms of data farmers might be willing to provide (at broader scale) for different types of purposes (e.g., research, crop insurance, regulation).

Because of the large role of agriculture in water use and water quality impacts (e.g., through fertilizer use), data from the sector are important for understanding and quantifying water generally. The issue of privacy becomes even more critical when considering how data can be acquired and systematically collated across regions.

WATER RISK

At the World Economic Forum in 2014, businesses ranked water crises as the third highest global risk. Industry uses water for applications such as fabrication, processing, washing, sanitizing, diluting, cooling, and transporting products. Nationwide, the paper, chemicals, petroleum refining, and primary metals industries accounted for 84% of the water used by manufacturing establishments, and thermoelectric power accounted for 45% of water withdrawals (although most of this water is returned). Most of the water (82%) withdrawn for industrial purposes is surface water.

Water issues create risks that cut across every industry sector and every type of service, and water conservation is beginning to be prioritized by industries. Population growth, climate change, the rise of a global middle class, and increased demand for energy, food, and consumables are all driving water risk—and these big trends are not going to go away.

Population growth, climate change, the rise of a global middle class, and increased demand for energy, food, and consumables are all driving water risk.

BUSINESSES AND WATER RISK

Water is a current business risk that is projected to get worse. The concept of water as a business risk (and opportunity) is starting to gain some traction in the marketplace, but it is not yet a core part of how most companies and supply chain partners view risks.

Companies span the spectrum in terms of their strategies to address water risks. At one end, some companies still have no strategy at all. Others a little further along the maturation spectrum have a strategy focused on water efficiency and water conservation. Further on the spectrum are the companies that are using a risk strategy for dealing with water at the facility level, including heavily weighting water-related risks to companies' social license to operate. Further still is the true leadership approach of pursuing a license-to-grow strategy, where companies align business strategy with water strategy and quantify the value of water.

Quantifying the economic and business value of water, in both the private and public sectors, can be helpful in making the case for treating water differently. Quantifying the value of water can include not just consumptive uses, but also ecosystem benefits, brand/reputational risks and benefits, and other factors. While the vast majority of such risk assessments are qualitative or categorical, several companies and organizations are working on risk quantification in various sectors and regions of the world; these efforts are hardly perfect, but they are a start.

Companies that are advanced are assessing water risks in their processes and supply chains, but understanding macro trends only takes companies so far. Companies need specific data that enables them to figure out how to apply those trends strategically to their businesses and how to take a risk management approach to water.

Companies always have to make choices and tradeoffs, and reputational and other risks associated with water should be part of that enterprise risk strategy process.

Some companies have developed real-time sensors to assess water quality in industrial processes and in wastewater, enabling more frequent and more accurate process adjustments, as well as significant water treatment cost savings. For companies that have agriculture in their supply chain, field-level data are incredibly important, but data from buyers can provide comparable quantitative, macro-trend data and information. Some companies are combining whatever public well-level data exists with proprietary data to create more accurate and informative water risk profiles that help them figure out which agricultural suppliers to partner with and where to divest. If a company does not understand where the water risks are in its supply chain, its growth prospects could be undercut.

Even when data are lacking, decisions have to get made. When making business decisions, companies always have to make choices and tradeoffs, and reputational and other risks associated with water should be part of that enterprise risk strategy process.

Leading companies understand that water risk is far more than just a social and environmental issue and that addressing it requires commitment at the board and executive levels. There may be a need for these companies to go even further, speaking out publicly on water policy, supporting good regulations, and working more collectively (as some in the beverage industry have started to do) to understand where water risks lie and to address cumulative impacts on water resources.

Companies that are heavy water users are also starting to look at trends in social media to gauge the reputational risks that can be discerned from how negative the online chatter about them is. Reputation and brand will be big drivers in getting companies to act, and social media data can be used as a kind of social sensor.

Whether water use reputational risk is a sufficient driver to affect consumer behavior remains to be seen, but ongoing droughts that affect particular commodities (e.g., almonds) could provide some empirical evidence.

Financial markets are not necessarily making it easier for companies (and others) to take action on water risk. Even though water security is a growing issue with companies, and even though water can have large reputational repercussions for companies, an astonishing number of deals to save water languish in the markets, while similar deals to save energy are multiplying. It seems as if there are higher hurdles for water deals to get done, though it is unclear if that is due to industrial users' skepticism or different levels of real or perceived risk. (Somewhat similarly, there are currently many things that municipal entities are doing with regard to climate change and water, including becoming more climate resilient and pricing water differently, for which financial markets have been punishing them.) Markets need to start reinforcing that these kinds of actions are good and desirable for the long-term.

INVESTORS AND WATER RISK

Investors are beginning to consider water risks as well, though it is unclear whether water risk is influencing investor decisions in a material way. While there are water funds and water indices, consideration of water in the finance world is a generation behind consideration of carbon. Once the finance community has decent data, it will likely become more engaged.

Investors understand that the biggest barriers to assessing water risk in their portfolios are lack of data and the difficulty of predicting the financial impact of water restrictions on an industry.

One of the key limitations for assessing water risk is the lack of broadly applicable yet meaningful tools, such as quantitative frameworks regarding water scarcity, planning tools to address issues of drought, and qualitative assessments to determine whether companies examine water risk and reflect that risk in their business strategy or use it to strategize growth management. Investors understand that the biggest barriers to assessing water risk in their portfolios are lack of data and the difficulty of predicting the financial impact of water restrictions on an industry.

Much higher quality data covering longer time periods at higher spatial resolutions are available. The challenge is aggregating these data from a variety of formats into a usable format for large-scale comparisons.

There are other approaches to evaluating and quantifying water risk, such as those developed by CDP and Bloomberg (*see box*). CDP sends questionnaires to companies to assess awareness of water chains and water resource management. The responses are collated by industry sector and country and can be accessed through a global report, an online interactive visualization tool, or both. Trucost's Water Risk Monetizer Tool estimates the effects of water costs on revenue in an effort to make the link between business risk and water risk.

Future versions of these tools might incorporate issues of water quality and regulation, which will require the development and synthesis of data that are more difficult to integrate than water quantity or availability.

WATER RISK ASSESSMENT TOOLS

The **Carbon Disclosure Project (CDP)** is one of the rare providers of a global platform for companies to share environmental data, including water supply data. It surveys companies to assess their awareness of supply-chain water use, degree of disclosure regarding water resources, and approach to managing those resources. Of the 312 companies with headquarters that responded to the survey in 2014, 35% had integrated water into company-wide risk assessment that incorporated both direct and supply chain operations; 9% of companies reported not examining water risk.

The **World Resources Institute's Aqueduct Water Risk Atlas** tool compiles 12 global indicators into three categories of risk (water quantity, water quality, and regulatory/reputational risk) to generate an overall water stress score. The indicators are interactively displayed on a map that allows users to compare scores across large regions and identify areas for further assessment. The data and maps are available for public use. Aqueduct is a great tool for a regional assessment of water stress (and used broadly for this purpose) but is not as optimal for local decision making, given that it provides river basin-level detail (covering hundreds of square kilometers) and uses large datasets from global studies to generate stress indicators.

Bloomberg's **Water Risk Valuation Tool** builds on Bloomberg's information on companies and WRI's Aqueduct tool to assess the baseline water conditions of a company based on the company's location and future water stress. This information is used to estimate the financial impacts to a company's stocks depending on whether the company reduces production or invests in capital expenditure to address water shortages. Initially, the tool's primary purpose will be to allow investors to note the risk to their investments and to start a conversation with companies about how they are managing their water resources.

Quantifying Water Performance

While some industry data on water are available (e.g., the water disclosure reports from CDP), those data tend to be focused on soft metrics (e.g., policy) more than quantified performance. Bloomberg terminals are starting to include a water consumption indicator, but investors increasingly are recognizing that simply knowing a company's water usage is inadequate, as it does not relay the true risks or impacts on water resources. For example, water use relative to water availability in a region or from available stores would be substantially more informative than simple water use. Leading investors are trying to look beyond the aggregate numbers to try to capture a company's true water dependence, piecing together information on the water sources the company relies on, the security of those water supplies, the company's wastewater discharge needs, the water-related regulatory and reputational risks, and the company's level of water stewardship (e.g., whether water policies are in place, whether water issues are dealt with at the board level or the facility level, etc.).

Investors would like independent third-party data on which companies and industries are operating in which places, the health of the relevant water resources, and the impacts of those companies and industries on those watersheds.

Beyond data from companies themselves, investors would like independent third-party data on which companies and industries are operating in which places, the health of the relevant water resources, and the impacts of those companies and industries on those watersheds. Translating scientific data so that investors could understand corporate impacts would be valuable, but investors are still far from having those data.

Conducting the intricate water analysis just described is very complicated and labor-intensive, in large part because water-related data from businesses is diffuse, imprecise, and often qualitative. Few investors are using water data or water analysis as part of their decisions. While some investors are interested in more of the environmental, social justice, and human rights elements of water—looking at investing through a sustainability lens—other investors tend to look solely at financial data. They may not need the information that environmental scientists have on water quantity, quality, and scarcity so much as they need to know how that affects company profitability and stock prices. The most valuable data for them are data based on familiar terminology, but investors have yet to identify the few key company water metrics on which they should focus. Similar to agriculture, the type and scale of available data do not match the type and scale needed by investors.

One industry that has been proactive in developing quantitative approaches to using water data is the insurance industry. For instance, Swiss Re Group has created an app that provides steps to prepare for (and to get insurance for) flood events. The Computer Sciences Corporation has developed a product called “ClimatEdge” for insurance agencies to better predict climatic events. ClimatEdge uses more than 2.5 terabytes of NASA satellite rainfall, soil moisture, atmospheric wind, humidity, and runoff data to predict flood events on a daily scale. These types of approaches are likely to become increasingly common as well as sophisticated with greater data availability.

WATER POLICY

Data can drive policy changes, and policy can likewise drive data generation, collection, analysis, and use. Policies, in turn, can also have a huge effect on water management strategies. As data capabilities and water risks evolve, there is a question as to whether water policies need to evolve as well.

INTERACTION BETWEEN WATER POLICY AND DATA

New data and visualizations can make complicated issues clearer and can drive policy by changing public opinion and creating space for policy revisions. The GRACE satellite images of groundwater depletion in California, for example, changed the public debate in the state. Non-point source pollution is the next frontier, as there is huge potential for new data, new sensing technologies, and new visualization tools to drive policy decisions. Data will be critical there to assess the success of nutrient and pollution reduction efforts. Real-time data can also be used in the water quality trading context; instead of trying to figure out what a best management practice might yield, trading can be based on what it actually yields.

New data and visualizations can make complicated issues clearer and can drive policy by changing public opinion and creating space for policy revisions.

Policy can also drive data, such as when governments require disclosure of data by regulated entities. California, for instance, changed state policy and required every city to report its water use monthly, with some basic guidelines on data and with the data being made public. Now there are NGOs and others analyzing and using that data in different ways.

In the policy world, there are probably water decisions we do not even know we should be making because we do not yet have the data. It would be helpful to think of the policy questions we want to answer and then work backwards to determine whether pulling existing data and synthesis together could answer them or whether there is some key data or synthesis missing. A vital part of that inquiry involves thinking about what level and certainty of data is needed. As noted before, different levels of data quality can be appropriate for different purposes.

There is a risk, though, that focusing too much on data could delay policy action; the call for data can sometimes be used as a stall tactic. Fundamentally, many of the big issues around water—in the United States and elsewhere—involve policy, and there is enough existing data to know that a lot of regulations are not working and that incentives are misaligned. At all levels, from local to federal, the desire for better data must be balanced against the need for action.

In the policy world, there are probably water decisions we do not even know we should be making because we do not yet have the data.

The challenge is establishing the quality assurance procedures and associated levels of veracity needed for the data to be used in a regulatory context. Non-government data—for instance, crowd-sourced and citizen science data—raise significant policy questions: Was an appropriate sampling protocol used? What types of data are appropriate for different types of policy? How much data validation is required for policy use? Should some organization or agency be expected (or required) to eventually own or certify the data?

The Federal Community of Practice on Crowdsourcing and Citizen Science, comprised of 31 federal partners, is developing strategies for improving the federal use of citizen science "for the purpose of enhancing agency mission, scientific and societal outcomes." Efforts are under way to test the quality assurance procedures using citizen science data. One is the Citizen Science Air Monitoring program, which is helping the EPA assess air quality conditions. Guidelines are still needed for how non-traditional data can be used in a policy context.

NEED TO UPDATE POLICY

The Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA) have served the United States well for decades, but they are not necessarily designed to handle new developments and technologies. The laws were written primarily to target the effluent that comes out of pipes and to make sure drinking water does not have harmful levels of pollutants. The laws were not written with algal toxins, fracking, and epic droughts in mind.

The CWA and SDWA also do not readily incorporate data gathered remotely, as regulations require a high level of data validation and verification, which can be difficult with remote sensing. The laws likewise are not designed to accommodate continuous monitoring. For instance, the NPDES permit program currently sets limits as single numbers that cannot be exceeded without penalty, but use of continuous data would likely require limits expressed as ranges or percentage exceedances. Regulations also tend to require monthly reports, whereas new reporting mechanisms may need to be authorized and created to take advantage of new technologies, such as electronic reporting of continuous data.

Improving Monitoring & Enforcement

Enforcement of water policy is complicated by the diversity of data collection agencies, the static nature of data collection in dynamic systems, the enormity of the systems that require monitoring, and the significant lag between data collection and data use, raising public safety concerns with undetected problems.

Consider enforcement in North Carolina of the Clean Water Act, under which states must undertake EPA-approved water quality monitoring. The state has more than 300 monitoring stations on its rivers, streams, and estuaries from which state personnel collect samples monthly for analysis of a range of water quality parameters (e.g., temperature, dissolved oxygen, nutrients, coliform). Using typical methods, measurement of these parameters can take days, constraining understanding of particular monitored waters and making sampling of a larger geographic range of waters prohibitively difficult and expensive. CWA monitoring is so labor- and time-intensive that only 29.6% of U.S. stream and river miles have been assessed. Similarly, 43% of all lake, reservoir, and pond acres have been assessed. Of those water-bodies that have been assessed, 53.7% of rivers and streams and 67.6% of lakes and reservoirs are considered impaired for their designated use.

The EPA and states will need to redefine which non-government-sourced water quality data are acceptable to include in enforceable statutes.

Static monthly sampling and delayed analyses mean that the CWA regulates numerous stakeholders rather than pinpointing problems and refining solutions. Big data analytics can help remedy this situation through use of real-time in-situ nutrient sensors and calibration of satellite images to water quality parameters.

For example, researchers in the Midwest are correlating the Thematic Mapper on the Landsat satellite to water clarity in lakes. In coastal zones, EPA researchers are using Hyperspectral Imager for the Coastal Ocean (HICO) satellite imagery to correlate concentrations of chlorophyll a, organic matter, and turbidity. These efforts require significant amounts of calibration, but they are dramatically increasing the temporal and spatial resolution of data on conditions of the nation's waters. This resolution, in turn, can strengthen CWA implementation by targeting the true sources of pollution.

Simultaneously, similar analytics can assess the best places for remediation and if remediation efforts are working. If big data analytics are to support monitoring efforts in accomplishing what the CWA intended, then states—which are legally responsible for data quality assurance—will need to update their data collection protocols.

Most importantly, the EPA and states will need to redefine which non-government-sourced water quality data are acceptable to include in enforceable statutes.

Like CWA enforcement, Safe Drinking Water Act (SDWA) enforcement is stymied by often static measurements in dynamic systems. Water distributers are required to monitor their water contaminants on various schedules according to contaminant type, water source (groundwater or surface water), and population size (larger populations require more drinking water monitoring). With more than 52,000 community water supply systems, 21,400 nonprofit non-community water supply systems (e.g., schools and hospitals), another 89,000 transient non-community water systems (e.g., campgrounds), and distribution pipes stretching more than 980,000 miles, the amount of information on the safety of drinking water is staggering. The SDWA regulates 91 contaminants, most of which are monitored on a quarterly schedule. Some of these contaminants, such as total coliform, pose a significant health risk, and thus the SDWA requires large utilities to collect as many as 480 samples a month.

When SDWA-mandated monitoring systems and protocols fail, there are public health ramifications. The more rapidly we can sample these large distribution systems for contaminants, the more outbreaks threatening public health can be avoided. Biosensors and toxin sensors are being deployed directly into drinking water systems and are improving the speed at which we detect problematic contaminants. Big data platforms can visualize the entire drinking water system (including source waters) and support quick response when a biosensor detects an anomaly. Ideally, a drinking water platform could be accessible to the public to check the most up-to-date information about drinking water and problem detection speed.

More broadly, federal water policies were designed in an era when data was limiting, when much of the currently available technology was neither available nor conceivable. Much of the early implementation of these federal policies was based on the inherent assumption that many pollutants could not be actively measured. These basic presumptions that underlie the core federal water statues (and environmental statutes in general, e.g., Endangered Species Act) are now becoming woefully out of date.

For instance, the CWA assumes that NPDES permit holders will be the primary entities measuring water quality of their emissions. This is valid when such measurements are logistically and technically difficult. But what happens when comparable measurements can be taken by smart phone, or by imagery via a private drone? What are the processes to be used by regulatory agencies to acquire, inventory, and make use of such diffuse, citizen science data? More basically, what is the regulatory authority of such data?

FLEXIBILITY IN POLICIES

Governments cannot respond quickly to technological innovation, new data streams, or changing conditions. The formality and importance of legal standards mean that governments cannot leap on a new technology, for example, until they can study the new technology and determine it to be better than existing approaches. Particularly when government agencies are risk averse, under-budgeted, and understaffed, governments are not going to be on the edge of data and technology innovation. Changes in technologies, data, and conditions are still going to happen, however, which means policies need to be designed or interpreted to be as flexible and responsive as possible (though regulators would have to determine the priorities where flexibility is needed).

As governments update their protocols, they should recognize that regulations cannot possibly anticipate every new source of data and so should be written flexibly enough to accommodate the data innovation that will occur.

Climate change is one of the drivers of the need for foresight and flexibility. For example, many places have policies for regulating the effects of water temperature on discharge and intake limits for power plants—and these policies and rules are predicated on conditions remaining constant. As warming progresses, though, the temperatures in rivers, diversion structures, and elsewhere will rise. A new normal will therefore have been reached that is out of step with regulations' baseline conditions. Therefore, flexibility should be built into policies to account for changing baselines. Similarly, for water quantity, the current rigid system needs to be made more flexible to enable sharing of water among users, in order to drive efficiencies and enable trading that can respond in real time to who needs what.

Policies and regulations that require particular monitoring technologies are likewise out of date and inflexible—akin to telling kids to use the Encyclopedia Britannica to do research. As governments update their protocols, they should recognize that regulations cannot possibly anticipate every new source of data and so should be written flexibly enough to accommodate the data innovation that will occur.

CONCLUSION

Faced with the range of pressing water challenges today, water agencies and industry now recognize the need to develop a better understanding of what data are available through different technologies coming to the fore, how those data can be standardized and integrated, and how risk can be assessed by industry and investors at the individual site level. This should be part of a new, coherent national water data policy.

Luckily, the 21st century is opening new opportunities in remote sensing, satellites, citizen science, and data exhaust, for example, which can provide new insights into water use and changes over time. This is particularly game-changing in the agriculture sector, which is going through a transformation with precision agriculture. Yet, while these new technologies show great promise, there are still significant hurdles to overcome: privacy concerns, data aggregation and integration, standardization, use and regulation of citizen-generated data, and updating policies to support the new world of big data for the benefit of society.

Farmers, businesses, investors, and policymakers are all important audiences for water data and data tools and should all continue to be active participants in this conversation, as we seek to move from the current state of being overwhelmed by data availability and limited synthesis to data-informed decision-making and water management across sectors.

Forums such as the Aspen-Nicholas Water Forum are an important piece of the process that provide space for diverse and visionary thinkers to collaborate and pave the way toward a transformed, world-class U.S. water system. Government at all levels, along with water utilities and major water users, must now join forces to better monitor and assess water availability and usage and to increase our national perception of, and appreciation for, the tenuousness of the water access we now take for granted.

APPENDIX I: FORUM AGENDA

THE ASPEN-NICHOLAS WATER FORUM
DATA INTELLIGENCE AND WATER SUSTAINABILITY

May 28 – 31, 2015 | Aspen, Colorado

The 2015 Aspen-Nicholas Water Forum will explore the opportunities and challenges that big data brings to measuring, managing, and monitoring water resources from aggregation to use in agriculture, manufacturing, municipalities, and public policy. If data can uncover patterns that otherwise go unobserved in water resource conservation and management, how should communities monitor water quality, what entities can and should be aggregating water resource data, who is in the best position to analyze this information, how can data from diverse sources be synthesized to form a coherent and revealing picture, and how should data intelligence inform policy creation? Can the increased amount of data solve today's pressing water conservation challenges to ensure sustainable ecosystems, resilient cities, a true value of water, and more secure infrastructure?

FRIDAY, MAY 29

Session One: The Big Data Frontier: Satellites and Simulations

What does big data mean today and can it improve the sustainable use and management of water across sectors? This opening session will frame the Forum by asking these introductory questions, while also diving into current and emerging types of water data available. Discussants will show emerging tools and visualization techniques of cutting-edge data from sources such as new satellites, combined with real-time modeling and simulation, to illustrate the potential of data integration. We will also address the questions and challenges related to use, aggregation, curation, and privacy that these new technologies pose to the sector.

Moderator: **David Monsma,** The Aspen Institute

Discussants:

Setting the Scene	**Martin Doyle**, Nicholas Institute
Global Simulations & Visualization	**Budhendra Bhaduri**, ORNL
New Satellites & Regional Simulations	**Jay Famiglietti,** UCI/NASA
New Tools from Private Industry	**Tyler Erickson**, Google, Inc.

Session Two: The Small Data Frontier: Crowd-Sourcing and Citizen-Scientists

This session will open our eyes to what's happening on the ground with crowd-sourced data from citizen scientists—today's micro data aggregators—and what is on the horizon. The real revolution in water data may not be in satellites, but in "data exhaust," or data byproducts generated in the course of normal business, a potentially powerful source of information. All of these data present novel opportunities for increasing the temporal and spatial resolution of observation, while increasing the public's role in collecting information and putting it to use. At the same time, challenges persist around evaluation of data accuracy and privacy.

Moderator: **Nancy Stoner,** Pisces Foundation

Discussants:

The Power of Citizen Science & Crowd-Sourced Data	**Nolan Doesken**, Colorado State University
Precision Conservation & Water Quality	**David Burke**, Chesapeake Conservancy
Data & the Smarter Community	**Brewster McCracken**, Pecan Street Inc.

Session Three: Smarter and More Resilient Cities

To address municipal water management concerns such as long term supplies, source water quality protection, sustaining headwaters for ecological health, preserving reservoirs, and stormwater runoff, while also combatting the impacts from climate change and increased weather events, water must be better monitored, measured, and managed. Are we making use of the full extent of water data that exists on a watershed scale from all sources? Increasing insights into water supply, use and reuse, and wastewater might increase the precision of investments, whether in grey or green infrastructure. Are there lessons to be learned from the energy sector's experience with developing smart grids, demand response, and the new energy innovation ecosystem? What synergies might exist when water and energy data are shared and integrated? How do we combine all of this to build smarter and more resilient cities?

Moderator: **David Monsma**, The Aspen Institute

Discussants:

Learnings & Connections to Energy	**Bryan Hannegan**, NREL
The Smart Grid for Water	**Trevor Hill**, FATHOM
Across the Board Utility Integration	**Marc Waage**, Denver Water
Understanding Water Use Habits	**Dominique Gómez**, WaterSmart

Session Four: Transforming Agriculture

The agricultural sector has been at the leading edge of putting water data to work, and as the largest user of water, has the potential to strongly influence water sustainability. Farmers are increasingly working with real time and high-resolution data to optimize decision-making around planting, fertilizing, watering, weeding and harvesting crops as companies continue to develop novel approaches for information collection and utilization. Can Ag provide lessons and insights for other industries in how to scale up innovations, while both addressing data ownership and privacy concerns and meeting regulatory requirements?

Moderator: **Gordon Binder**, Nicholas Institute

Discussants:

Transparency & Data Monitoring	**Alan Boyce**, Materra, LLC
Water as a New Crop	**Disque Deane**, Water Asset Management
Increasing Precision of Water Use	**Daniel Rooney**, Trimble

SATURDAY, MAY 30

Session Five: Evaluating Water Risk: From Supply Chains to Portfolios

Water permeates all commodities, whether in food or fiber, as a component of energy production, or as a form of transportation. There is potential water risk in all sectors and in almost all investments. Many industries are attempting to evaluate the risk in their supply chains, just as investors are attempting to quantify their exposure to water and climate risk. Such evaluations are dependent on the availability of useful information. Efforts to engage data in water risk evaluation, whether in a supply chain or in a portfolio, are currently rudimentary. Can increased use of data on water availability, quality, and quantity better capture the water risk that is material to the bottom line? Can intelligent use of data provide greater transparency to customers and investors? Can it forecast the true value of water?

Moderator: **Martin Doyle**, Nicholas Institute

Discussants:

Impacts of Water Risk	**Monika Freyman**, Ceres, Inc.
Corporate Risk Case Study	**Ryan Barr,** E&J Gallo Winery
Market-Transforming Innovation	**Jonathan Grant**, WaterTAP
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Session Six: The Future of Water Policy

The Clean Water Act and Safe Drinking Water Act—both over forty years old—were sagely developed in a world without ubiquitous computational power.

Do these policies, and their state counterparts, reflect the best approach to managing water resources and ecosystems, given the dramatic changes that have occurred in our ability to monitor and measure water? Will new capacities to measure and monitor water quantity and quality alter how policies are implemented? If so, does this merit revisiting the basic approaches to water policy in general? Which level of agency–federal, state, or local–should be charged with regulating, generating, curating, and managing data? Or is there greater benefit in keeping data generation and aggregation at a more local level, such as at the watershed scale or open-source community? Will rethinking the measurement side of water quantity and water quality markets lead to their more effective use, or cause us to rethink their role altogether?

Moderator: **David Monsma,** The Aspen Institute

Discussants:

Federal Efforts	**Ellen Gilinsky**, U.S. EPA
Utility Water Management	**Biju George,** DC Water
Maintaining Water Supply	**James Eklund**, Colorado Water Conservation Board
Sustaining Ecosystems	**Margaret Bowman**, Walton Family Foundation

Session Seven: Creating Intelligence – Integration & Co-Creation

Will more data lead to integration or fragmentation? Will it lead to more of the same, or transitions and transformations? This session will pull together different threads of thought, with participants exploring the possibilities and challenges around water accounting systems, integration of information across federal, state and local agencies, and the role of the corporations, NGOs, citizen scientists, and open source communities.

Moderator: **Martin Doyle**, Nicholas Institute

Discussants:

Integrating Public Data	**Jerad Bales**, USGS
Water Data-Mining Tools	**Ahmed Badruddin**, WatrHub Inc.
Aggregation in Natural/ Social Systems	**Kristal Jones,** SESYNC

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APPENDIX IV: ACRONYMS

AMI	Advanced metering infrastructure
ATP	Agricultural technology providers
BMP	Best management practice
CoCoRaHS	Community Collaborative Rain, Hail and Snow Network
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
CWA	Clean Water Act
eDNA	Environmental deoxyribonucleic acid
EPA	Environmental Protection Agency
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
GIS	Geographic information systems
GPM	Global Precipitation Measurement Mission
GRACE	Gravity Recovery and Climate Experiment
HICO	Hyperspectral Imager for the Coastal Ocean
IBM	International Business Machines Corporation
ISO	International Organization for Standards
LiDAR	Light detection and ranging
mPING	Meteorological phenomena identification near the ground
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
SCWA	Sonoma County Water Agency
SDWA	Safe Drinking Water Act
SMAP	Soil moisture active passive
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WBCSD	World Business Council for Sustainable Development
WRI	Water Resources Institute