Adaptation in the Water Sector: Science & Institutions

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Abstract: Water management activities involve a complex and interconnected web of science, infrastructure considerations, societal expectations, and institutional limitations that has evolved over time. Much of the water management system's current complexity developed in response to the interests of local water users and land owners, historical water supply and demand issues, political demands, and water quality and environmental considerations. Climate change poses a new set of questions for water managers and may require more flexible solutions than those that have evolved historically. Although the implications of changes in the climate on water supply and demand are recognized (if not well quantified), ongoing changes in temperature and precipitation, as well as the linkages between environmental and societal factors, lead to major uncertainties in future conditions. New tools, techniques, and institutions will be needed to sustain water supplies for communities and watersheds in the future.

People have been managing water and adapting to surpluses and shortfalls since the dawn of civilization, and especially since the early origins of agriculture. There is evidence across the globe of thousands of years of dam-building and canal construction to direct water toward crops of various kinds. Though the tools water managers use today are dramatically more sophisticated than those used in the past and the scale on which water managers work is much larger in almost all cases, the activities are still very much the same: managing floods and shortages (droughts) through harvesting and storing water above or underground, delivering water across long distances through pipelines and canals, and using a variety of technologies to increase water-use efficiency. Over the last one hundred and fifty years, the invention of turbine pumps and the development of multiple sources of energy have led to increased pumping of groundwater and the creation of significant linkages between water availability and energy usage.

The story of adaptation to surpluses and shortages is not new: climate and weather have always varied

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on timescales ranging from days to weeks to decades and even centuries, and there have always been "surprises" like the dust bowl of the 1930s or the recently discovered fifty-year megadroughts (documented through tree ring studies) in the 1100s.[1] But climate change and a variety of rapidly evolving social factors add new dimensions to the challenges of managing water supplies. These challenges derive from the fact that water managers must plan for a future of increasing uncertainties, including potentially escalating storm intensity and changes in flooding and droughts interacting with natural variability on multiple timescales. Changes in the demand for water exacerbate the already complex water management picture, while other social, economic, and technological trends also affect water demand across the United States. For example, rapid changes in water-use patterns are related to changes in social values, such as recent decisions to preserve instream water flows for the environment, recreation, or the use of Native nations.

Underlying changes in land use and shifts in both the location and type of water demand are factors of great concern to water managers in some regions. For example, changes in agricultural irrigation practices in the Great Plains and Southeastern United States are seriously impacting groundwater availability, as are new practices to extract natural gas in Texas, the Great Plains, and the Northeast. Some of these changes in water demand may be related to climate change, because recent droughts have caused an increase in irrigated agriculture as opposed to dry-land agriculture as farmers struggle to maintain yields. But social factors have also impacted water use in these regions in dramatic ways; consider, for example, policy-driven decisions to increase biofuel development. It is clear, therefore, that the challenges of water management are multifaceted and require a sophisticated understanding of both natural and social processes.

Increases in emissions of greenhouse gases (such as carbon dioxide and methane) are trapping more heat in the atmosphere, leading to changes in the drivers of the hydrologic cycle. These hydrologic changes are primarily due to higher air, surface, and water temperatures. At higher temperatures, water evaporates more rapidly from plant leaves, soil, and the ocean's surface, and the atmosphere can hold more water vapor. These changes affect both the demand for water (for example, for urban and agricultural irrigation) and the amount of runoff in rivers. Because of the combination of higher temperatures and higher water-vapor levels in the atmosphere, additional escalation of the hydrologic cycle (including both increased rainfall intensity and longer dry periods) is expected over time – even if global greenhouse gas emissions are reduced relatively soon. Regardless of efforts to manage global emissions, additional increases in the average global temperature due to emissions of carbon dioxide and other gases are a virtual certainty.

Even with ambitious reductions in carbon emissions (called "mitigation" by climate scientists) it will take decades to slow the pace of climate change. This is due in part to the very slow rate of removal of carbon dioxide in the atmosphere: carbon emissions currently in the atmosphere will be there for hundreds of years,[2] so even low-emissions scenarios used in climate modeling show an initial increase in total carbon monoxide concentrations and continued warming through the middle of this century.[3]

Changes in precipitation and runoff, snow and ice melt, and sea-level rise are associated with many of the observed and expected impacts in regions and sectors. The water-resources sector (comprising environmental, economic, and water management systems) is in turn impacted by these changes. Water therefore has the potential to play a fundamental role in both contributing to and resolving problems stemming from climate variability and change in most economic sectors. For example, water is a critical component of all natural habitats and one of the most important inputs to agricultural systems. It supports municipal development, extractive industries and manufacturing, energy generation, and transportation systems (particularly transportation via oceans and inland waterways). Even relatively minor changes in the hydrologic cycle can have major ramifications that ripple across the globe through energy and food systems or manufacturing supply chains. Most aspects of hydrology and water management institutions are extremely complex, so it is not surprising that there is still some debate about which components of the observed changes are related to climate change and which are connected to other underlying causes.

One source of uncertainty related to climate change is that certain categories of impacts have no precedent in human experience. This means that the tools that have historically been used to adapt to climate variability may no longer be sufficient to deal with the hydrology of the future. Though there have been unusually warm and cool periods in the Earth's history, they have not occurred since vast cities were built along the coastlines of every continent. We also now have an interconnected global energy, transportation, economic, and communications infrastructure that could be interrupted by extreme and unprecedented weather events. Water managers who have based their understanding of possible future floods on the past thirty to one hundred years of records now know that their decisions must take into account flooding outside of the scope of those records. And although we do have tree ring data that show the past history of droughts, including droughts more intense than anything in recent history, it will be possible to exceed even the megadroughts of the past in the coming era of warmer temperatures.

For water managers, uncertainties come from multiple sources, and not knowing how much change to expect or how many variables will be changing simultaneously is challenging. Some of the uncertainty relates to our limited ability to estimate timing of the projected impacts, including the challenge of predicting an event with an understood probability (for example, a one-in-five-hundred-year event) when the probability itself may be affected by uncertainties that cannot yet be calculated.

On the other hand, managers are used to making decisions without perfect information, so in some ways, they are very well prepared for the challenges that lie ahead. Navigating climate variability – the year-to-year changes in conditions – requires very sophisticated management tools and practices, including seasonal climate projections. Water managers know that the envelope of the past century's "normal" climate variability is already being exceeded in many regions, but it is difficult – if not impossible – to project with accuracy how much more the extremes (or the "tail ends" of the statistical distribution of events) will extend.[4] Indeed, it is these extremes – long periods of severe drought, or storm-related intense rainfall and flooding – that are most disruptive to water supply systems. The customers of water management systems expect water to come out of the tap on demand, but extreme events such as floods, droughts, wildfires, and coastal storm surges often interfere with these expectations.

Although water problems are already a major challenge in many parts of the world, some experts contend that virtually any water management problem has a solution and that implementing it is primarily a question of how much money and energy are available. For example, it is possible to desalinate seawater and pump it hundreds or even thousands of miles to thirsty water users in the deserts of Africa, or to tow icebergs from the Arctic to island nations that lack freshwater, but these solutions are generally viewed as unsustainable on large scales or over long distances because of cost, energy requirements, and environmental impacts. It is also possible – and in some regions, increasingly common – to reuse municipal wastewater for irrigation and even for drinking water. A relatively cost-effective adaptation option in drier areas is to store stormwater underground to enhance groundwater supplies; there are multiple technologies available to accomplish this. However, although technological solutions to water-related problems have improved health, sanitation, quality of life, and access to food across the globe in dramatic ways, there are limits to technological solutions and many concerns about the negative effects of water management projects on biodiversity, cultural values, and other resources. For these reasons, efficient conservation practices are among the most effective ways to manage the increasing disparity between supply and demand in some regions and generally have fewer unintended consequences than other options. But even conservation has consequences. For example, an increase in irrigation efficiency may reduce return flows (water returned to the stream after overapplications from agriculture) to rivers or to groundwater aquifers, or dry up a riparian area with high habitat value.

Though a wide array of adaptation options is available, ranging from changes in behavior and the development of social support networks to changes in technology and institutions, there are also several challenges to implementing them. One challenge for adaptation planning is that solutions often must be individually tailored to take into account the local hydrologic and regulatory context, not to mention cultural, political, and economic considerations. A solution that works well in one location or region is often completely untenable in another, making great ideas difficult to transplant from one region to another. The range of options available varies dramatically based on economies of scale, access to information, the quality of leadership in the region or community, and availability of financial resources, as well as the political and cultural history of the region. Some water managers may have a host of adaptation options available to them, while others may be severely constrained.

Perhaps the most important barrier to adaptation is the complexity of water management institutions, which are notoriously impenetrable and seemingly nonsensical to external observers. For example, in many regions of the Western United States there are both "wholesale" water supplies coming from federal and state water projects and "retail" water supplies that are delivered to municipal, industrial, and agricultural customers by both public and private water companies. Many individuals and companies have their own groundwater wells or surface-water diversions, which are subject to different rules than those that apply to the "water providers" delivering water to retail customers. Within a given area, there may be irrigation districts serving agricultural users, dozens of private water companies, multiple municipal water suppliers, and a host of individual well owners. For example, in the greater Tucson, Arizona, metropolitan area (including associated rural communities in the same watershed), there are over one hundred and fifty municipal water companies, regulated under a variety of municipal, state, tribal, and federal laws and policies, as well as a host of internal policies and operating constraints. Some suppliers are also subject to oversight from the Arizona Corporation Commission, which regulates for-profit utilities.

To add to all of this complexity, the legal premise for establishing water rights is different in every state, so solutions developed in one state are often not readily transferable to another. Water-rights laws restrict water withdrawals and use in multiple ways. This means, for example, that the institutional capacity to solve water-supply problems through transfers across state lines, river-basin boundaries, or even within the same watershed is often highly constrained. In many cases there are restrictions associated with moving water between sectors or from one type of use to another (for example, agricultural to municipal uses); and there are often limitations associated with moving the "point of diversion" of river flow from one place along a river to another. Water rights in some states are allocated based on historic use – the "first in time, first in right" premise – which is not conducive to a flexible response to rapidly changing economic and climate conditions. Others have used land ownership in the vicinity of rivers as a mode of allocating water rights: the "riparian" doctrine. In California, some surface-water rights are more closely aligned with this approach, but there are multiple allocation systems depending on whether the use and the right existed prior to the state water rights system established in 1914, whether the water comes from federal or state water storage or distribution systems, and whether the rights are within specific basins whose water rights have been adjudicated through the courts. In general, water-rights systems work to resolve disputes and conflicts among users within a system. However, they are completely inadequate to respond to large-scale or rapid changes in supply availability.

Some states manage their water rights primarily through administrative (government) agencies, while others make most of their water-rights decisions through the courts. In Western states there are hundreds of sovereign tribal nations with their own water-rights and delivery mechanisms, and their water-use practices commonly interact in both positive and negative ways with the interests of other landowners in the vicinity of reservations.

Further, while states allocate surface and groundwater rights, the federal government generally regulates water quality (unless the authority to manage water quality has been specifically delegated to the state). This separation of water quantity management from water quality regulations results in multiple adaptation hurdles that might otherwise be avoided. For example, the use of municipal wastewater or "effluent" has been emerging for decades as a solution to water-supply problems in dry regions. But efficient use of this source is controversial in some areas despite evidence that careful treatment and reuse, especially for outdoor irrigation purposes, is possible without health effects – so water quality management agencies are frequently operating at odds with those who manage water-supply availability. These institutional problems are often viewed as barriers to adaptation to climate change. In fact, these barriers to adaptation are exceedingly well documented – much more so than the opportunities that may also result from adaptation to current and projected changes in the climate.

A variety of federal laws have a direct impact on adaptation opportunities in the water management sector. Among them are the Clean Water Act, the Safe Drinking Water Act, the Endangered Species Act, and the Clean Air Act, along with multiple federal agency–focused rules and regulations that affect the activities of leading federal water management agencies such as the Army Corps of Engineers and the Bureau of Reclamation. In rivers that generate hydropower, the Federal Energy Regulatory Commission provides an additional overlay of regulatory considerations. All of these regulations protect the health and safety of the nation's drinking water supplies for human use, as well as protecting the environment and habitat of endangered species, but in some cases they may not include the degree of flexibility that would be ideal for maximizing adaptive capacity and achieving water management objectives.

Conflicts often arise when rules for protecting aquatic species (like the silvery minnow in the Rio Grande or the salmonids and Delta smelt at the mouth of the Sacramento–San Joaquin Rivers) run counter to the interests of offstream water users. It is instructive to look at the case of the Sacramento–San Joaquin Delta in order to truly appreciate how regulatory activities intersect with the local "decision context," along with ongoing changes in land use and climate, creating a series of unanticipated consequences.

Climate-change uncertainty is only one of a number of sources of uncertainty in natural resource decision processes. The environmental and water-supply conflict within the Sacramento–San Joaquin Delta (the Bay Delta) provides a vivid case study of the complexity and uncertainty in water management decisions and the compounding effects of climate change. The Bay-Delta system has seen nearly four decades of intense political, legislative, and legal conflict, all centered on the tension between reliable water supplies for people and environmental protection.[5] In part, this conflict stems from decades of using a symptom-based approach (as opposed to a systems-based approach) to natural resource management; it also provides an important lesson in the need to understand the context in which decisions about adaptation are made. The management challenges in this case, like many others, are complicated by an array of overlapping legal and institutional issues, including multiple federal and state agencies with jurisdiction over various components of the system and no effective institutional authority to coordinate and manage the decision process.

Efforts to find a solution to the Bay-Delta conflict over the past few decades have focused on the most recent symptom of deteriorating environmental health: declines in populations of threatened and endangered species and a reduction in water-supply reliability for both the state and federal water projects. However, the problems in the Bay-Delta system have their origin in one hundred and fifty years of state and federal policy decisions. In the 1850s, Congress authorized a series of "Swamp Land Acts," providing land to those who would commit to draining and making use of the region's swampland. This policy and ensuing implementation efforts paved the way to the loss of more than 90 percent of the wetlands in California's Central Valley. In the early 1900s, a flood-control levee system was developed in the Central Valley, not only to provide flood protection but also in part to flush out sediment and debris from the destructive practice of hydraulic mining.[6] These narrow, leveed channels contributed to the loss of more than 95 percent of the Central Valley's riparian habitat. Additionally, the system has been populated over time, both intentionally and unintentionally, with a wide array of nonnative plant and animal species. The net result of these and many other factors is a highly altered resource system with little natural resilience. It is on this "nonresilient" system that the effects of climate change will be overlaid: higher flood peaks; sea-level rise; more intense, warmer storms; and warmer air and water temperatures.

The Delta has been called "the lynchpin in California's water-supply system," supplying water from Northern California reservoirs through the State Water Project and the Central Valley Project to urban Southern California, part of the Bay Area, and the San Joaquin Valley. The water supply from these projects supports more than $400 billion of the annual economic activity of the state and irrigates several million acres of highly productive agricultural land. The Delta is also the largest estuary on the West Coast of the western hemisphere, supporting vital West Coast salmon runs as well as a wide range of native plant and animal species.

Additional risks are associated with subsidence (sinking) of the land surface of many of the islands in the Delta. Some islands are now twenty feet below sea level, partly as a result of decomposition of the peat soils. They are protected by levees that have a high probability of failing in an earthquake or storm surge, especially in the context of sea-level rise. Areas of the Delta and the Central Valley are at risk for catastrophic flooding, which could have dire economic consequences. The physical and biological management challenges are further complicated by multiple biological opinions related to endangered species from separate federal agencies, federal court intervention regarding implementation of these opinions, and increasingly heated partisan conflict. In light of all this complexity, it is nearly impossible to identify problems that can be attributed to climate change (or climate variability) alone. However, it is clear that climate change is adding to the risk and uncertainty in the natural resource and water management system.

The climate change–related water management challenges in the Delta are not just about precipitation and runoff; they also relate to water temperature and the condition of the watershed. There are many unanswered questions about what California's future water supply could look like. How do these factors interact? As hydrologic drivers change, vegetation changes, resulting in potentially unanticipated feedbacks to the hydrologic cycle and the ecosystem. Is it possible to anticipate how these interacting factors will affect California's ecosystems? There is a critical need for this kind of integrated research in decision processes.

Water temperatures are going up, which could negate the habitat-management gains made through multiple other restoration efforts, because higher temperatures result in reduced oxygen and other chemical changes in the water, as well as more algae and bacteria. How can we know in advance when we are approaching thresholds beyond which endangered species cannot survive? Can water management in California continue to function if endangered species are declining and the Endangered Species Act (ESA) remains in its current configuration? It appears that the relatively inflexible requirements of the ESA and the needs associated with the water management system are in conflict – and not just in the Delta. Yet the ESA is essentially a proxy for environmental health, which makes it the most important tool currently available for promoting environmental sustainability objectives, even if the tool may be blunt and sometimes poorly used.

The ESA is not designed to deal with changes in baseline climate conditions. For example, until there are no more Delta smelt left, more and more restrictions on water management can be anticipated even if the smelt's decline is not directly related to the actions of water users. Ocean conditions, including the Pacific Decadal Oscillation,[7] have been correlated with populations of anadromous fish (fish that migrate from the oceans to the rivers to spawn). Further, even after multiple decades of study, California water managers do not know how many smelt there are or specifically where they are on a seasonal basis, which makes managing them very challenging. How can the cause and effect of individual management options in the rivers be evaluated in such a dynamic environment? Is adaptive management even possible in the context of all of this complexity?

How can California adjust to losing snowpack, prepare for potential levee failures, manage fish decline with changing water temperature and salinity, and deal with increasing concerns about meeting energy and water demand for a growing population, all in the context of ongoing statewide economic issues? It is clear that existing institutions are not up to these challenges, let alone able to respond to sea-level rise and the potential for earthquakes at the same time.

In this era of multiple stresses, we cannot afford to "strand investments" and spend money on infrastructure that may never be needed. For example, the iconic "fortress approach" to protecting low-lying cities by building seawalls around existing infrastructure is likely to fail eventually and will certainly have dramatic environmental effects. But facing the potential impacts of another Hurricane Katrina or Superstorm Sandy–like event, there is a need to find robust solutions that solve multiple problems, particularly in urban areas where there is significant investment.

After decades of working to establish a state-federal collaboration to manage all of these issues and to establish institutions capable of collective decision-making, most of the Bay-Delta conflicts remain unresolved. However, a great deal has been learned about managing the boundary between science and policy, as well as about adaptive management in complex decision contexts. And although water conflicts remain, scientists and decision-makers are finding ways to work together on environmental issues. California has been perhaps the most successful state in linking climate science to policy decisions, as evidenced by the passage of Assembly Bill 32, which limits future greenhouse gas emissions in the state. The evolution of this linkage began with an assessment process (the "Scenarios Project") involving decision-makers and scientists, which could serve as a model for other states to address, mitigate, and adapt to climate impacts in the absence of other federal legislation.[8]

Given the scientific, environmental, regulatory, and social context within which water managers operate and the associated barriers to adaptation, institutions clearly must innovate to manage risk and facilitate adaptation. The following section presents some institutional solutions that could help address water management challenges.

Many who have studied water management institutions believe that market forces can resolve many of the inefficiencies in water distribution and lead to major improvements in matching supply and demand in an era of increasing pressure on finite water supplies. There is evidence in Australia, for example, that establishing well-defined water rights that are tradable on an open market can actually increase the net value of agriculture, even under drought conditions.[9] Environmental policy researcher Bonnie Colby and others have analyzed the degree to which water markets have developed in the Western United States and market systems' utility for addressing climate change and related shortage issues.[10] Although water banks and other kinds of water markets have emerged in specific watersheds – and have in many cases achieved their desired objectives – their utility is limited.

Multiple authors have suggested that pricing mechanisms are underutilized, noting the direct relationship between increases in water cost and increases in efficiency of water use. However, others have noted the limitations of markets and pricing mechanisms in protecting environmental interests and the interests of those who are economically disadvantaged. Unconstrained markets can in theory lead to "economically efficient" outcomes, but economically efficient solutions are not the same as socially acceptable, environmentally sensitive, or sustainable solutions. Clearly, water pricing is an important tool in the water management toolbox and water markets can enhance flexibility in water-rights systems, but water markets and pricing mechanisms alone will not result in socially acceptable outcomes.

There is significant inertia in existing water management systems, at least in part because many economic and social decisions have been made within the existing regulatory framework. Businesses, municipal water companies, and farmers have all made capital investments based on expectations about the availability of water supplies, and these investments are often dependent on the assumption that water management institutions will remain stable. Major changes in regulations, even if they are broadly supported, are extremely difficult to implement, because there are always winners and losers, and those who anticipate becoming the "losers" in the context of proposed institutional changes are often vocal and litigious. History shows that major changes in water management systems often occur in response to emergencies rather than through farsighted investments in preparedness. A critical question is how we can increase the flexibility of existing water management systems in the face of growing challenges before the system fails. We must also find a way to flesh out the role of science and scientists in helping managers with adaptation.

A critical issue in climate adaptation is helping managers understand what possible future conditions they may need to be prepared for, and how they can wade through the torrent of available data and projections to get to truly useful information. The need to close the gap between science and decision-making in the climate arena has generated a number of experiments in adaptive management. In all of the successful cases, it is clear that a focus on building trusted relationships between those who generate scientific information and those who use it is a critical foundation for decision-making. Yet it is also clear that it is difficult to scale up these individual relationships and successful practices to the level required for adaptation across the water management sector.

In many fields, "science translators" are emerging to help connect scientists and decision-makers as they navigate differences in language, training, and context. Science translators help to identify scientific information that is truly useful for specific decisions and help stakeholders get access to appropriate data and tools for specific sectoral applications. For example, in California, support for water- and climate-related decisions has been provided through the California Applications Project (CAP), which is a National Oceanographic and Atmospheric Administration (NOAA)–funded effort to link university researchers and federal data sources to specific needs of decision-makers within regions. CAP includes researchers from Scripps Institute of Oceanography, the U.S. Geological Survey, and NOAA's Western Regional Climate Center. Science translators are often found in universities and consulting firms, but recently a number of nongovernmental organizations (NGOs) have also been developing climate-related adaptation tools for managers and trying to assist by building training programs.

There have been several deliberate attempts to expand the cadre of science translators: for example, through cooperative funding programs to train postdoctoral students and to enhance the function of "boundary organizations" that help manage the interface between these very different cultures.[11] "Decision-relevant" science has become much more visible in the budgets of federal science agencies as they recognize the importance of informing their own adaptation activities as well as those of communities and businesses across the United States. This is quite evident in the U.S. Global Change Research Program's (USGCRP) Strategic Plan for 2012 – 2021, which emphasizes "informing decisions," "sustained assessments," and "communication and education" as important pillars of their thirteen-agency climate research agenda.

A (very) small portion of the USGCRP's $2.6 billion investment in climate observations and research now goes to building climate science translation capacity, both within the USGCRP coordination office itself and within specific federal agencies – notably the National Oceanic and Atmospheric Administration; the Department of the Interior (DOI); and most recently the U.S. Department of Agriculture (USDA). NOAA's Regional Integrated Sciences and Assessments (RISA) program is the most mature of these investments, with eleven centers across the country; the CAP is one of the NOAA RISAs. Stakeholders who have worked with the program often note that the support of RISA staff has been critical to building awareness of climate issues as well as implementing solutions, and there are now several publications evaluating the effectiveness of the RISA efforts. But rising concerns about the need to ramp up adaptation capacity has resulted in building new Climate Science Centers, Landscape Conservation Cooperatives, and Climate Hubs within the DOI and USDA as well. Despite the expansion of these programs, the demand for "climate services" and for help from science translators in these centers far outpaces these programs' capacity to meet it.

One example of an innovative water management solution is the Arizona Water Institute (AWI). An entirely different set of water supply and regulatory challenges faces the state of Arizona, where an innovative science-translation organization was created to support water management objectives. Although funding and political issues led to its closure in 2009, the AWI showed significant promise in bridging the gaps between water managers, regulators, and scientists at Arizona's three universities. It was an important experiment in institution-building in support of adaptation that can serve as a model for others aiming to enhance adaptation capacity.

Arizona has been known for decades for its innovative water management activities. Although water issues facing the state are daunting and challenges continue to increase in the face of population growth and climate change, the state's commitment to long-term water supply availability has resulted in billions of dollars of investment in renewable supplies through the Central Arizona Project (bringing surface water from the Colorado River), groundwater recharge and recovery programs, and municipal effluent reuse. Arizona has also developed innovative regulatory programs, including the 1980 Groundwater Management Act (which requires sustainable groundwater use within five "active management areas") and the Arizona Water Banking Authority (which incentivizes augmentation of groundwater supplies).

However, despite the existence of hundreds of water specialists and climatologists across the three state universities, Arizona's water managers were not taking advantage of their scientific capacity prior to the establishment of the AWI. The AWI was formed through a governor's initiative in January of 2006 and included Arizona

State University, Northern Arizona University, and the University of Arizona. The primary driver for this initiative was sustaining Arizona's water supply, but other incentives for creating AWI also included the development of technologies and practices that could support water sustainability in arid regions more generally. This unique partnership, which also included three state agencies – Water Resources, Environmental Quality, and Commerce – provided access to hydrologic information for water managers, supported communities, and developed technologies to promote water sustainability. To ensure relevance to the private sector and other government interests, the Salt River Project (the state's largest water and electric utility) and the Governor's Office were also engaged in the AWI's leadership.

Managing relationships between the universities and the state agencies was probably the most challenging aspect of the AWI approach, but building the institutional connections proved to be an important asset in creating useful partnerships that were focused on real-world solutions. Again, building long-term relationships of trust within the science community and between scientists and stakeholders is a serious challenge but also a necessary prerequisite to successful climate adaptation efforts.

The AWI conducted a survey of local, county, state, and federal governments, Indian tribes, watershed alliances, farmers, water companies, NGOs, and private industries in order to establish research themes. This survey demonstrated strong interest from multiple sectors in collaborating with the AWI and resulted in six major focal areas that are likely to be useful topics for any water sustainability or adaptation program:

- Building a hydrologic information system to enhance access to water information in the state;
- Advancing water quality and treatment technologies;
- Promoting aquifer management and sustainability;
- Providing watershed and regional technical assistance and facilitation;
- Studying the expected impacts of climate variability and change; and
- Studying the interconnections between energy and water systems.

The AWI built strong relationships between the universities and water managers across the state, and thirty "real world" research projects were initiated within three years, each involving at least two universities and a minimum of one external stakeholder. AWI staff managed each project to ensure that the expectations of scientists and stakeholders were realistic and the outcomes were both useful and delivered in a timely way.

Although the AWI did not change either the underlying challenges of limited water supplies and population growth, or a wide range of institutional challenges, it did provide a hopeful and relatively inexpensive approach to adaptation through building networks that connected social and physical scientists within existing academic institutions with public- and private-sector decision-makers. Given the magnitude and complexity of the issues water managers face, networks of climate experts and adaptation professionals such as the AWI are emerging as a leading model for solving current and future challenges.

With the intent to help resolve many of the same science translation issues, NGOs have been stepping in to fill gaps in the knowledge system in regions and sectors across the country, including, for example, the Public Policy Institute of California (PPIC) and the California Water Foundation (CWF). The PPIC's water program forms teams of interdisciplinary researchers to focus on current water problems and bring the best available information to decision-makers.[12] The CWF's efforts are aimed at translating information into specific policy action; recent activities of the CWF include developing statewide groundwater management policies and legislation (adopted in 2014) responding to rapidly changing water-supply conditions.[13] Particularly as the resources available from federal and state agencies shrink, the role of foundations and NGOs in promoting environmental protection and more adaptive water management practices is expanding.

Although adaptation in the water sector is associated with innumerable challenges, there are just as many opportunities for innovation. In light of the expanding uncertainties associated with climate change, it is critical to develop better pathways for scientific information to reach decision-makers. The efforts of federally supported investments in climate science translation (such as the RISA program) and institutions that are designed to connect science and decision-making (such as the AWI) provide reasons to be optimistic that solutions to water management challenges are achievable. Studying lessons learned in California and Arizona in managing major water-supply problems is one source of useful knowledge in preparing for an uncertain future. Institutional flexibility and relationship-building are at least as critical to building sustainable water management systems as improvements in scientific understanding.

ENDNOTES

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