THE FUTURE OF GROUNDWATER

A REPORT FROM THE 2017 ASPEN-NICHOLAS WATER FORUM

Duke
NICHOLAS INSTITUTE
FOR ENVIRONMENTAL POLICY SOLUTIONS

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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 2017 Aspen-Nicholas Water Forum was the sixth 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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TABLE OF CONTENTS

PREFACE

The last decade has brought a dramatic shift in awareness of groundwater and our expectations for its management. But historically, any groundwater was deemed to be "so secret, occult and concealed, that an attempt to administer any set of legal rules would be involved in hopeless uncertainty, and would be, therefore, practically impossible."[1] This management challenge stems, at least in part, to past technological limits to understanding groundwater systems and to slow recognition and remedying of critical problems in them. There are no burning rivers or dry lakes to capture the public's attention. And yet, groundwater is a critical water resource, providing for half of the nation's drinking water supply and most of its irrigation water. Although significant management challenges remain, emerging innovations and technologies have the potential to improve our stewardship of groundwater.

To understand the management opportunities and challenges that groundwater presents, the Aspen Institute's Energy and Environment Program and Duke University's Nicholas Institute for Environmental Policy Solutions focused this year's Water Forum on the future of groundwater. The annual Aspen-Nicholas Water Forum serves as a platform for addressing domestic water challenges in the 21st century. The 2017 forum focused on exploring the present condition of groundwater, the evolution of that condition, and opportunities for transitioning to more sustainable use of groundwater resources.

Since the 1950s, many aquifers have been pumped at unsustainable rates, leading to sustained depletion and, consequently, stream flow losses, saltwater intrusions, and land subsidence. Aquifers with fast recharge rates typically experience water quality challenges because water from the surface can flow quickly into the ground, carrying contaminants and pathogens. In recent years, technological advancements and innovative management practices have suggested strategies for dealing with this problem.

Those strategies are captured in this forum summary, written by the Nicholas Institute for Environmental Policy Solutions at Duke University and the Aspen Institute. Not all views on the strategies were unanimous nor were unanimity and

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[1] Frazier v. Brow, 12 Ohio St. 294, 311 (1861)

consensus sought. Forum participants and sponsors are not responsible for this summary's content.

We thank the following sponsors for their generous support of the forum: S.D. Bechtel, Jr. Foundation, Water Asset Management, the Walton Family Foundation, the Cynthia & George Mitchell Foundation, National Renewable Energy Laboratory, Arizona State University, National Association of Water Companies (NAWC), and E. & J. Gallo Winery.

The Aspen Institute and the Nicholas Institute will continue to collaborate on development of pathways to address the state of the U.S. water system. The numerous challenges in the U.S. water sector today—from the drought in California to water quality problems in the Chesapeake Bay to groundwater depletion in the Ogallala Aquifer—will be the subject of the Aspen-Nicholas Water Forum in the years to come.

EXECUTIVE SUMMARY

In May and June 2017, 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—including thought leaders from the private sector, government, academia, and non-governmental organizations—represented expertise in industry, finance, philanthropy, government, academia, agriculture, food and technology companies, investors and entrepreneurs.

Aquifers are a natural form of infrastructure that provides substantial services, including collecting water from irrigation and floods, filtering out many contaminants and pathogens to make water suitable for drinking, and providing long-term and short-term water storage without evaporative losses. Replacing the functions of aquifers through traditional infrastructure projects, whether treatment plants or reservoirs, would come at staggering costs. Managed carefully, aquifers are a cheap natural infrastructure that could be used to provide a stable water source for generations. However, without proper management, this natural infrastructure will deteriorate and become unusable, increasing costs of, and reliance on, almost all other aspects of our water systems.

The impetus of the 2017 Aspen-Nicholas Institute Water Forum was to identify the current state of groundwater and to spearhead development of a shared vision for the future of groundwater resources in the United States. The consensus was that groundwater needs to be sustainably developed, meaning groundwater use must be balanced among economic development, environmental health, and quality-of-life needs in a way that allows our children and grandchildren to enjoy a use comparable to today's. In many instances in which aquifers have been depleted and negative consequences have become visible across the landscape (e.g., in the form of drying streams, land subsidence, and saltwater intrusions), simply moving to sustainable development might not suffice. Instead, a moonshot goal would be to couple rising aquifers with a growing economy.

Today, there are more opportunities than ever to pursue the sustainable development of groundwater. Technological improvements in data collection (satellites and cheaper sensors and more sophisticated models) are steadily advancing our measurements and understanding of groundwater systems. Those same improvements allow us to generate data visualizations and other tools to increase public awareness and understanding of groundwater systems as well as provide data needed to underpin robust water markets. Moreover, low interest rates mean we can invest in large-scale aquifer improvement projects such as aquifer storage recharge and on-farm flooding technologies to help raise groundwater levels. Finally, treatment technologies are increasingly effective in removing contaminants from groundwater, though avoiding contamination remains the best option.

We live with a finite amount of water, and our management of it must be intentional and fully accountable. Across U.S. regions, groundwater use will, is, or has reached a sustainability tipping point. Even if rudimentary, the data and information to demonstrate the trajectory of groundwater levels and quality exist. Change requires political will, stakeholder incentives and support, financial resources, and innovation.

Two related challenges to moving forward are lack of impetus for doing so and lack of a shared vision. Each aquifer is composed of different geologic and groundwater characteristics that influence contamination and depletion impacts, which often are unmonitored and unnoticed. As groundwater impacts have become more visible (and litigated), states are being forced to create regulatory structures to address them. However, the local nature of groundwater management—reflecting the fact that groundwater is local, use is local, and problems with that use typically present as local—has inspired no overarching national vision for groundwater. Nevertheless, diverse shareholders might be able to develop such a vision based on the following ideals:

- Groundwater use must be balanced among economic development, environmental health, and quality-of-life needs for future generations.
- Groundwater and surface water should be integrated, where and when possible, for management decisions, regulations, and policies.
- Groundwater needs to be constantly "visible," not just when it is at the center of a problem or crisis.
- Trust, underpinned by transparency, is central to changing management approaches.
- Approaches that have been successful in one place should be tested elsewhere, recognizing translation and scalability challenges.
- Creating efficiencies through groundwater markets must be balanced with ensuring some level of access equality.

KEY FINDINGS

Managing groundwater in the coming decades will require an alignment of forward-thinking governance, innovative public funding and private sector financing, and educated stakeholders—including the public. In turn, that alignment will require a shared understanding of the value of water and of the funding required to provide it in quantities and of a quality sufficient to meet society's needs. This report summarizes the May-June 2017 Aspen-Nicholas Water Forum discussions, offering various approaches to groundwater sustainability.

1. To date, groundwater has been managed for sustained depletion. We need an alternative goal: simultaneously rising aquifers and a growing economy.

The current practice in many U.S. regions is to use groundwater at rates that exceed recharge, leading to long-term, sustained depletion. We believe there is great economic opportunity and potential for innovative strategies to enable BOTH economic development AND groundwater sustainability by making them commensurate goals.

2. Proactive groundwater management balances the needs of all users—from ensuring access by domestic households to securing food supply to meeting energy demand to protecting the environment—while accounting for climatic variability and population growth to ensure groundwater is available for use for future generations.

Aquifers are a natural form of infrastructure that provide amazing services such as collecting water from irrigation and floods, filtering out many contaminants and pathogens to make water suitable for drinking, and providing storage without evaporative losses. Managed correctly, groundwater provides a cheap natural infrastructure that could be used to provide a stable amount of water for generations. However, without proper management, this natural infrastructure can deteriorate and become unusable, requiring substantial financial investments to collect, store, and treat water for use.

3. Aquifers may span thousands of miles, but the management and impacts of groundwater use are context-specific, given unique geologic conditions and water use characteristics. Although aquifers are complex and unique, the consequences

of groundwater contamination and depletion are not. A portfolio of already-developed solution sets (market, technological, regulatory) is available and can be tailored to fit within existing policies and regulations.

Approaches for moving toward groundwater sustainable development include:

- Ongoing regulatory experiments;
- Opportunities to develop and expand groundwater markets—particularly with a cap-and-trade structure in areas with depleted aquifers—even in currently unmetered regions;
- Emerging data collection techniques and modeling and water technologies that continuously improve our understanding of groundwater resources and options; and
- Fit-for-purpose water use whereby wastewater are treated only to the level required for a specific activity, resulting in reduced groundwater withdrawals.

4. Groundwater is often locally managed, although the consequences of groundwater depletion can span large regions. Boutique solutions will not suffice to solve large-scale problems, making it important to identify solutions sets, including conservation, markets, and water funds, that are scalable.

Three strategies found to be replicable and scalable are conservation, markets, and water funds. Conservation is a strategy that can include all water sectors and individuals. Conservation efforts will look different in each sector, their goal being to reduce water use as economic development continues. These strategies tend to have high upfront costs with long-term savings. Markets have the capacity to create water use efficiencies; identifying types of water markets suitable for different regulatory structure and groundwater conditions would allow markets to be replicated quickly between regions. Water funds generate revenue through property tax, sales tax, private donations, utility fees, and so on that are then used for source water protection through land purchases and easements.

5. It is critical to build trust and transparency that leads to collaboration by, and education of, decision-makers and the general public.

Many successful groundwater management programs have occurred in situations in which there was (1) an external force or crisis, (2) a strong stakeholder group, and/or (3) trusted community leaders. One of the greatest shortcomings of groundwater governance has been the failure of decision makers to grasp the central importance of the human dimension of water management, that is the goals, incentives, rights, practices, and constraints of stakeholders and their need for trusted leaders and messengers. Part of building trust involves transparency. Now, more than ever, emerging satellite technologies and data visualizations provide an opportunity to educate by make data more accessible to all.

Education is critical because groundwater cannot be seen or directly experienced and only enters the public consciousness when there is a problem such as land subsidence and dry wells. Many rural, domestic wells are already suffering from groundwater problems but don't have the information, resources, and/or understanding of these systems to effectively engage these problems. Little public education and investment in groundwater occurs before invisible problems become visible. And at that point, there are high costs and long time horizons to fix the problem.

Communication of groundwater issues to the public requires communication of (1) the problem and the solution; (2) urgency of addressing the problem; (3) linkage of impacts to personal experiences and costs; (4) the responsibility of the collective "we" for creating the problem and the responsibility of the individual to improve the situation; and (5) the message needs to be repeated by trusted communicators within a community or sector.

6. Those most immediately vulnerable to groundwater problems are often the smallest contributors to the problem, and the government regulatory structures most likely to protect those communities are not well organized to do so.

An estimated 44.5 million people (14 percent of the population) rely on private wells, and there are 130,000 privately owned groundwater systems. Domestic households and small systems often don't have access to surface water, particularly in already allocated systems, and are dependent on groundwater for their entire water supply. These individuals and communities may not have the resources to treat their groundwater should standards change or wells become contaminated, nor can they afford to drill deeper wells when groundwater levels drop. They are the smallest users of groundwater; however, they often bear the brunt of the increasing costs to access water. This situation begs the question of how to include private individuals and small systems in conversations about managing groundwater resources as well as conversations about policy and regulations. Often it is only the large water users that have the resources, bandwidth, and incentives to engage in decision-making and management.

INTRODUCTION

In May and June 2017, 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—including thought leaders from the private sector, government, academia, and non-governmental organizations—represented expertise in industry, finance, philanthropy, government, academia, energy, agriculture, food and technology companies, investors, and entrepreneurs. Sessions explored the current state of groundwater, the evolution of that state, and the growing opportunities to move from sustained groundwater depletion toward sustainable groundwater development through ongoing policy and regulatory experiments, market opportunities, and technological advancements. This report summarizes those discussions.

AN ALTERNATIVE FUTURE FOR GROUNDWATER

A natural form of infrastructure, aquifers provide substantial services, including collecting water from irrigation and floods, filtering out many contaminants and pathogens to make water suitable for drinking, and providing long-term and short-term water storage without evaporative losses. Replacing the functions of aquifers through traditional infrastructure projects, whether treatment plants or reservoirs, would come at staggering costs. With careful management, aquifers are a cheap natural infrastructure that could be used to provide a stable water source for generations. However, without proper management, this natural infrastructure will deteriorate and become unusable, increasing the costs of, and reliance on, almost all other aspects of our water systems. For example, groundwater depletion can result in aquifer compaction; reducing the amount of water the aquifer can store in the future. Lowered groundwater elevations increase the costs of pumping for irrigation. An aquifer that is either directly contaminated or affected by saltwater intrusion may eliminate groundwater as a resource entirely, or it may require expensive treatment processes and take decades to fully restore. Thus, proactively sustaining existing aquifers and restoring those that have been harmed are critical undertakings.

MOONSHOT GOAL:
Rising aquifers and a growing economy

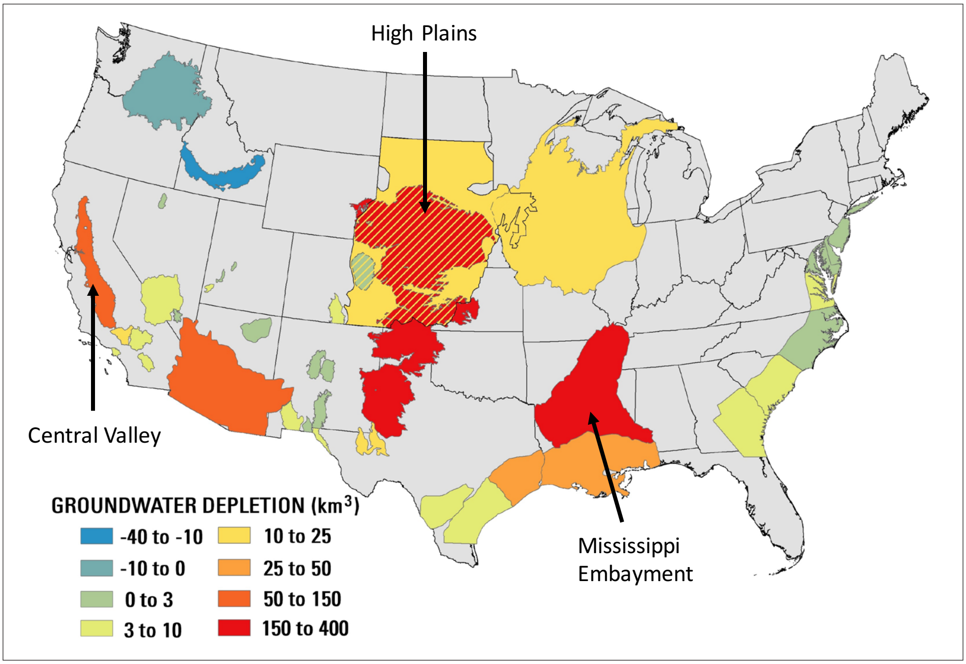
Sustainability, as used here, means resource conservation, putting groundwater to its best uses, exercising good stewardship, and ensuring our children and grandchildren will have the same opportunity to use groundwater as we do today. Importantly, it means balancing groundwater use across economic development, environmental health, and quality-of-life needs. As one participant noted, "If you asked me how my marriage was and I said sustainable – that's not great." We may want or need to aim for a goal beyond sustainability—a "moonshot goal," namely, rising aquifers and a growing economy. This goal is relevant across the nation, but also at the regional, and even local level.

TODAY'S GROUNDWATER CHALLENGE

CURRENT STATE OF GROUNDWATER

Groundwater, stored in aquifers throughout the United States, has been continually depleted; an estimated 264 Tgal (810 MAF) of groundwater were removed between 1900 and 2008.[2] This volume is about twice that of Lake Erie and could account for 2.8 mm of observed sea-level rise.[3] The three most depleted aquifers as of 2008 were the High Plains, Mississippi Embayment, and Central Valley aquifers (Figure 1). Each of these aquifers serves as the primary source of irrigation in major agricultural regions: the nation's primary sources of grain (High Plains), fruits and vegetables (Central Valley), and rice (Mississippi Embayment).

Figure 1: Groundwater Depletion from 1900 to 2008 (USGS 2013)[2]



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[2] Konikow, L. (2013). Groundwater depletion in the United States (1900-2008). *USGS Scientific Investigations Report 2013-5079,*

[3] Konikow, L. (2015). Long-term groundwater depletion in the United States. *Groundwater*, 53 (1), 2-9.

Groundwater provided roughly 25 percent of freshwater withdrawals in 2010; accounting for nearly half of domestic supply and the majority of irrigation water. This heavy use has primarily affected quantity rather than quality (with important geographic exceptions). Nationwide, groundwater tends to be of high quality; only 23 percent of sites tested by the United States Geological Survey (USGS) exceed a human health benchmark, and most of the contamination arises from geologic sources.

GROUNDWATER CHALLENGES

Groundwater is an invisible resource, presenting challenges for monitoring, modeling, and basic understanding. Groundwater science has grown tremendously over recent decades through the development of novel monitoring technologies and improved computational technologies that enable sophisticated modeling. Groundwater data from sources ranging from new satellites to low-cost well monitoring have begun to produce new insights; however, communicating how groundwater works to the wider public and decision makers remains difficult.

A second challenge is the significant spatial and temporal lags between the occurrence of groundwater harms and detection of those harms. Each aquifer's geologic and groundwater characteristics influence the impacts of depletion and contamination, and we don't fully understand the long-term impacts of contemporary groundwater practices or events. The impacts of groundwater pumping, for instance, can take more than a decade to surface and a longer time to remedy. Managing a resource today for impacts that become visible decades later presents significant challenges in terms of education, funding, and management practices.

Groundwater is out of sight, and unless it is monitored (which it often is not), the slowly spreading impacts from depletion and contamination may not be immediately noticed. As visibility (and litigation) of groundwater impacts has increased, states have had to create new regulatory structures, creating a third challenge: the multiple governance structures to which large aquifers may be subject. In many cases, groundwater is managed through sub-state institutions. For example, in North Carolina, capacity use areas were developed in 2002 in the coastal plain region to address groundwater depletion. In Texas, 99 groundwater conservation districts have regulatory authority to manage groundwater, and the Edwards Aquifer Authority was formed to protect endangered species and address land subsidence issues. In California, water replenishment districts were established to conserve groundwater and recharge aquifers to halt saltwater intrusions.

Diverse regulatory practices can enable concentrated problem solving, but it can also thwart opportunities for investments in technology and infrastructure because it limits economies of scale and introduces uncertainty about investment return.

Consider the consequences of the autonomy of the 99 groundwater conservation districts in Texas. In these districts, groundwater rights are linked to property ownership rather than owned by the state as water rights. Therefore, groundwater use by industries and privately-owned utilities located within multiple groundwater conservation districts is managed under different regulatory structures, entailing significant transaction costs to translate practices or technologies between regulatory structures within a single state.

Groundwater management has also been hampered by the habitual separation of surface water from groundwater, both conceptually and in terms of regulations, policy, and law. Identifying the point at which groundwater ends and surface water begins is challenging and often arbitrary. Historically, most states have chosen to manage and regulate surface water but have ignored groundwater. This approach has resulted in a hodge-podge of disconnected, and at times conflicting, regulations and policies between surface water and groundwater.

The regulations and policies may be disconnected, but groundwater and surface waters are not disconnected: groundwater has a direct impact on the volume and quality of surface water resources and vice versa. As groundwater is depleted, the fraction of water withdrawn from groundwater storage decreases, while the amount of water "captured" from streamflow increases. Over the long term, 85 percent of water pumped comes from stream capture; only 15 percent comes from storage depletion.[4] The implications of streamflow depletion become points of litigation in areas where surface water rights have been fully allocated and river compacts were signed prior to recognition that groundwater and surface water are linked. Streamflow depletion also reduces habitat in groundwater-dependent ecosystems, particularly wetlands, for migratory birds and aquatic species. The loss of that habitat can lead to regulatory actions. Different regulatory schemas make it a challenge to holistically manage water resources.

Conversely, over-allocation of, or allocation changes in, surface water can have significant impacts on groundwater levels. With completion, in the 1960s, of the Central Valley Project, many agricultural communities shifted to using more surface water than groundwater, which allowed aquifer levels to rise. However, starting in 1992, that trend was reversed by several changes in surface water management, from reallocations from the Mount Shasta reservoir to passage of legislation to protect freshwater and marine ecosystems. As surface water availability to the Central Valley declined, agricultural communities relied more heavily on groundwater. This reliance, coupled with almost a decade of dry conditions, led to steeply declining groundwater tables. These outcomes are not surprising when surface water is highly

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[4] Konikow, L. & Leake, S.A. (2014). Depletion and capture: Revisiting "the source of water derived from wells." *USGS Staff Published Research.* 832.

regulated while groundwater is treated as a common pool resource. At the same time, this drought-driven crisis has resulted in a profound convergence of several regulatory requirements regarding groundwater, surface water, and runoff. This regulatory convergence has been enabled by advancements in data entry, quality controls, and analytics that are creating insights and water efficiencies.

DROUGHT CRISES: BRINGING GROUNDWATER TO THE SURFACE

Much of our understanding and legislation of groundwater is built on key insights gained during droughts as groundwater depletion becomes more intense and the consequences of increased pumping become visible. The recent multi-year drought in California, for instance, increased the nation's awareness of groundwater resources and led the state to regulate groundwater for the first time (see the Sustainable Groundwater Management Act). Indeed, the drought highlighted a water management reality: groundwater typically serves as a hydrologic buffer during drought. When droughts occur, surface supplies are depleted and curtailed, and large water users turn to groundwater to fill the gap. In California, groundwater supplies 40 percent of water used during a normal year and 60 percent used during drought.

The passing of SGMA is emblematic of how states are coming to grips with 21st century conditions: hydrologic extremes are becoming more common, population continues to grow, infrastructure is difficult to permit and finance, and society desires to provide more water to ecosystems. These constraints on water resources require collaborations among industry, farmers, utilities, NGOs, academia, and government to determine how to best conserve water resources, to recapture more groundwater through aquifer storage and recovery (ASR) and on-farm flooding infrastructure, and to holistically meet ecosystem needs.

Like the western United States, the eastern United States is not immune to multi-year droughts. Dendrochronology (tree-ring) reconstructions of historic hydrology indicate that the eastern United States has been unusually wet over the last 40 years compared to the past few centuries. But it is likely to be drier in the future. Even under these relatively wet conditions, farms in the eastern United States that are reliant on groundwater-based irrigation have already experienced groundwater depletion since the 1970s. Even in the humid, subtropical climate of Arkansas, Louisiana, and Mississippi, over-pumping has produced large cones of depression in the Sparta Aquifer. Similarly, over-pumping in the coastal plains of North Carolina resulted in cones of depression, saltwater intrusions, and dewatering in the late 1990s and early 2000s.

SUSTAINABLE GROUNDWATER MANAGEMENT ACT (SGMA)

In 2016, California emerged from its driest drought in 1,200 years.[a] Two years earlier, that drought had spurred passage of the Sustainable Groundwater Management Act, making California the last western state to adopt groundwater regulation. SGMA recognizes the diversity of aquifers and groundwater issues in California by identifying 127 groundwater basins and making them subject to regulation by local agencies authorized to define groundwater sustainability and to enforce plans to achieve sustainable development over a 20-year period.

SGMA defines sustainable groundwater management as the management and use of groundwater that can be maintained without an undesirable result such as persistent lowering of groundwater levels, saltwater intrusion, degraded water quality, land subsidence, and surface water depletion. This definition allows localities to pursue sustainable development of their local groundwater basins by adapting management plans and regulations to their specific conditions. Because SGMA is in its infancy, it is unclear whether it will achieve widespread sustainable development of groundwater resources. If it does, it would have a significant and positive economic impact on California.

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[a] Griffin, D. & Anchukaitis, K.J. How unusual is the 2012–2014 California Drought? *Geophysical Research Letters* 41 (24): 9017–9023.

Groundwater depletion is not simply a western or arid regions issue; it is a national issue. And because it is a national issue, different states and regions have grappled with the problem with different mechanisms. New policies, innovation, and emerging technologies present opportunities to ensure groundwater resources are available for use in the future.

GROUNDWATER GOVERNANCE

FEDERAL GROUNDWATER POLICY – FOCUS ON WATER QUALITY

The federal government provides some regulatory oversight for groundwater quality protection, but it leaves groundwater allocation (i.e., quantity) decisions within the domain of states. Federal laws and regulations pertain to groundwater quality as it relates to protecting drinking water; the 1974 Safe Drinking Water Act (SDWA) protects water quality at the point of the treatment plant, but not within the aquifer. Of the country's 150,000 public water systems (most of which are very small), 87 percent rely on groundwater resources.

The SDWA regulates potential contaminants that might enter groundwater in three ways. First, its underground injection control (UIC) regulations are designed to prevent the contamination of underground sources of drinking water from fluids injected into the ground. In the United States, there are nearly 750,000 UIC-regulated wells, and nearly 1 trillion gallons (3.1 million AF) of fluid are injected annually. Second, the 1996 amendments of the SDWA require source water protection assessments for groundwater, although with no follow-up requirements. Third, the "Ground Water Rule" of 2006 aims to protect from pathogens those public water systems that use groundwater as a source of drinking water without disinfection and that are susceptible to fecal contamination.

When groundwater-dependent ecosystems contain endangered or threatened species, the federal government may pass additional regulations to manage groundwater through the Endangered Species Act.

Other federal regulations aim to protect groundwater from contaminated land surfaces. These regulations include underground storage tank laws, the Resource Conservation and Recovery Act to manage solid and hazardous waste, and the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) to clean abandoned hazardous waste sites. Many of these land-based federal regulations are implemented and tailored by states.

Ultimately, federal protection of groundwater quality is about protection of drinking water quality. Newer approaches to groundwater management, such as aquifer storage and recovery, will need to fit within SDWA to ensure that groundwater quality standards are not impaired for future generations.

STATE GROUNDWATER POLICY – FOCUS ON WATER QUANTITY

Federal groundwater regulations have evolved to focus on water quality, but state groundwater policies and regulations are built around water quantity and allocation. Nationally, there are five broad, overlapping approaches to managing groundwater allocations.[5]

1. **Absolute Dominion Rule (absolute ownership or rule of capture):** This rule treats groundwater as a property right whereby the landowner also owns the water underneath his or her land and can withdraw it at any rate, even if adjoining property owners are harmed. In many instances, exceptions have been built into the rule such that malicious and negligent pumping are not permissible.

2. **Reasonable Use Doctrine:** This doctrine allows a landowner to withdraw and use groundwater beneath his or her property as long as the use is "reasonable." The landowner has a qualified, rather than an absolute, right to use groundwater. The Restatement (Second) of Torts is similar to the reasonable use doctrine but allows for liability when withdrawals lower the water table; interfere with lakes, rivers, and streams dependent on groundwater; or constitute more than the owner's reasonable share. This rule is aimed at protecting small well owners from high economic costs due to excessive pumping at high capacity wells.

3. **Correlative Right Doctrine:** This doctrine is similar to the reasonable use doctrine with the added caveat that all landowners over a shared aquifer have coequal or correlative rights to the water, and none can extract more than their fair allotment or injure other's rights. The share is usually based on the amount of acreage owned relative to the total area overlying the aquifer. Once again, the right to groundwater is tied to property rights. Only California seems to apply correlative rights in the sense of proportion sharing; other states (e.g., Nebraska and Oklahoma) use correlative rights only during periods of scarcity.

4. **Prior Appropriation Doctrine:** This doctrine fully transitions water from a property right to a water right. Groundwater belongs to the state and is allocated on the basis of when water was taken from a source and how much was applied to a beneficial use (see Colorado Groundwater Rights).

5. **Regulated Riparianism:** This governance structure requires water users to obtain a time-limited permit from the state based on an evaluation of the reasonableness of the proposed water use. A common motivation for this form of governance is to authorize the use of water on non-riparian land. The permitting system creates a mechanism for long-term planning at the state level.

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[5] Dellapenna, J. (2013). A Primer on groundwater law. *Idaho Law Review* 265; Villanova Law/Public Policy Research Paper No. 2013-3042. and Joshi, S. (2005). *Comparison of groundwater rights in the United States: Lessons for Texas* (Master of Science Thesis at Texas Tech University).

COLORADO GROUNDWATER RIGHTS

Colorado became a pioneer in holistically managing groundwater and surface water when, in 1914, the Colorado Supreme Court recognized that groundwater and surface water are linked and declared that the prior appropriation doctrine pertains to the sources of streamflow, including groundwater. This ruling was upheld in 1951. Colorado would like to move toward a water budget incorporating both surface water and groundwater resources, particularly because it is involved in several river compacts legally requiring specific volumes of water to flow downstream to neighboring states. However, the data and the legislative regime would need to evolve for such a budget to exist.

EVOLUTION OF STATE AND LOCAL GROUNDWATER POLICY FROM CRISIS TO CRISIS: TEXAS CASE STUDY

Groundwater management at the state and local scale have historically been defined by two management approaches. First, groundwater was originally assumed to be inexhaustible; therefore, its use was not heavily regulated and a model of "sustained depletion," or continually decreasing groundwater levels, was established. Second, the resulting groundwater crises, rather than proactive groundwater management, have driven policies and practices. However, there is often opposition by those whose livelihood has become dependent on unlimited access to groundwater; oftentimes resulting in the piecemeal addition of regulations stripped of most of its regulatory power. Texas illustrates how such policies and practices have developed.

Like many states, Texas, followed the 1861 Ohio court ruling that groundwater was "so secret, occult and concealed, that an attempt to administer any set of legal rules would be involved in hopeless uncertainty, and would be, therefore, practically impossible." This ruling was used by the Texas Supreme Court when a railroad company accessed a shallow aquifer during a drought in 1901 in Denison and caused nearby domestic wells to run dry. The court ruled for the railroad company, indirectly establishing groundwater as a property right (rather than a water right) in the state of Texas.

The 1930s Dust Bowl began to raise concern in Texas over the impacts of agricultural pumping on groundwater; however, the agricultural community fought against legislative efforts to regulate groundwater use. In 1949, the state legislature decided to make groundwater a local management issue and enabled the formation of groundwater conservation districts (GCDs), effectively making groundwater management a local issue.

After a wet period, drought conditions returned, and in 1996, several small towns ran out of water. The Texas legislature revamped water planning and transitioned from the top-down (state water plan) to a bottom-up approach (16 groundwater management areas were formed to develop regional water plans). The bottom-up approach had greater capacity to involve stakeholders and to develop comprehensive plans. Districts within a groundwater management area are required to collaborate to define desired future conditions of groundwater resources as well as to provide the enforcement capacity for GCDs to set targets and cap groundwater permitting. Texas provides assistance through groundwater modeling and stakeholder convening because there were legislative incentives to get scientific consensus to support policy recommendations given to stakeholders and decision makers. Although collaboration of scientists, stakeholders, and policy makers is not time efficient, it does lead to consensus and often to strengthened relationships among water sectors. Planning by the 16 groundwater management areas have received mixed reviews. Many believe that groundwater caps are not sufficiently stringent and say that rural areas have lost groundwater access while urban areas have gained it.

Today, there are more than 100 GCDs, many following county boundaries and many regulating groundwater use differently. Approximately 10 percent of the state still allows unrestricted pumping. A significant challenge is that most preliminary groundwater regulations were established decades ago and are difficult to significantly alter now. New litigations reference initial laws, many of which were made before we have begun to understand how much groundwater is available, how fast it recharges, how contaminants move through the system, or how groundwater and surface water are linked. Thus, historic regulation systems have the potential to be reinforced through litigation. Case in point: a 2012 decision by the Texas Supreme Court that directly established that groundwater is a property right owned by the people and not a water right owned by the state, a decision in line with the 1901 railroad ruling. The result of this ruling is undercutting of GCDs authority to curtail groundwater pumping. Many want water regulation to follow oil and gas law, essentially returning unrestricted use of groundwater under property to property owners. Many are suspicious of the science and allocation rules.

LOCAL GROUNDWATER POLICY AND SMALL-SCALE SYSTEMS

Although states establish broad groundwater legislation, it is up to local entities to create and implement supporting regulations. Often these regulations are developed with the input of industrial stakeholders reliant on water supplied through municipalities, thereby linking local governance of groundwater with industry expectations and practices. In the past, industrial water users viewed themselves primarily as customers and thus sought to minimize the cost of water, using their large purchasing power as leverage. However, attitudes have shifted, and water sustainability has become part of the business decision-making process (see Proactive Industrial Governance).

PROACTIVE INDUSTRIAL GOVERNANCE

Uncertainty regarding groundwater governance allows industry to play a more proactive role in sustainable groundwater development. Industries are increasingly recognizing that there is a cost to sustainably developing water supplies and that as water becomes scarcer, the cost to access water will grow, affecting economic development. Therefore, industries are becoming increasingly interested in investing in water conservation efforts. For example, some industries are working with growers to implement more efficient irrigation technologies and practices, while others are supporting projects that aid in groundwater recharge. Industries are partnering with government to improve groundwater resources. In Florida, a cost share fund promotes industry, and utilities have adopted innovative water management technologies such as aquifer storage recharge.

An additional transformation in industrial water use is the increased use of "fit-for-purpose" water rather than reliance on municipal supplied water, which is often treated to drinking water quality standards. Fit for purpose means the water resource will be treated only to the level required for a particular activity. Through significant developments in water treatment technology, industrial water users are able to recycle their used water and to treat it just to the point of usability for their own internal purposes. The net effect of this practice is reduced freshwater use and use less energy for treatment and pumping. The only downside for the water utility is the potential loss of water demand from a large user.

Unconventional oil and gas activity provides an example of fit-for-purpose water use. Each well requires water to stimulate the release of hydrocarbons. In areas such as the Permian Basin in Texas, freshwater supplies are limited, and companies need to rely on a variety of water sources, including brackish water, wastewater from municipalities, produced water reuse, and, as a last resort, freshwater supplies. Brackish water and wastewater from municipalities are the most readily available alternative sources. Use of the wastewater from unconventional oil and gas activity is a larger management challenge than acquisition of water for hydraulic fracturing. The technology for cost-effectively treating produced wastewater laden with organics, salts, and naturally occurring radioactive materials (NORMS) is not yet present in all unconventional plays. Texas faces a scalability challenge in reusing produced water because the groundwater is managed by more than 100 conservation districts with different regulatory structures. However, reuse—likely fit-for-purpose reuse—is necessary to manage this wastewater because it is extraordinarily expensive to treat, and UIC wells have a finite capacity before unintended consequences, such as induced seismicity, occur.

DOMESTIC GROUNDWATER USERS

At the most local of levels sit domestic water users—individual wells at the scale of a home. An estimated 44.5 million people (14 percent of the population) rely on private wells, and there are 130,000 privately owned groundwater systems. Domestic households and small systems often don't have access to surface water, particularly in already allocated systems, and are dependent on groundwater for their entire water supply. These individuals and communities may not have the resources to treat their groundwater if standards change or if the wells are contaminated, nor can they afford to drill deeper wells when groundwater levels drop. They are the smallest users of groundwater; however, they often bear the brunt of the increasing costs to access water. Similar to climate change, those most immediately vulnerable to groundwater problems are often the smallest contributors to the problem, and the government regulatory structures that are most likely to protect those communities are not well organized to do so.

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How can private individuals and small systems be included in conversations about groundwater management and about policy and regulations? Often it is only the large water users that have the resources, bandwidth, and incentives to engage in decision-making and management. Small drinking water systems don't have that luxury and often need to put limited resources toward the largest ongoing crisis. Furthermore, most water resources, including groundwater, are often managed at the basin level. This scale may exceed the planning and management capacity of under-resourced communities. Groundwater conservation districts and management areas at a county level may provide a scale for under-resourced communities to engage more productively and to have a louder voice at the table.

ONGOING POLICY AND REGULATORY EXPERIMENTS: WHAT CAN TRANSLATE ELSEWHERE?

While aquifers can be large and spread across multiple states, the impacts of use are slow to spread and manifest locally. Therefore, it has been local entities that have been the most engaged in experimenting with groundwater management, innovative policy and regulatory structures, and local-state government interactions.

Many localities face the same kinds of groundwater issues and could share solutions between regions. Essentially, each locality is a laboratory experiment on groundwater governance. However, successful approaches can be repackaged in the context of existing regulatory and legislative frameworks. All such efforts will confront socially tricky issues like trust as well as technically simple issues like monitoring.

GOVERNANCE AND TRUST

Many successful groundwater governance programs have occurred in situations involving one or more of the following: an external force or crisis, a strong stakeholders group, and trusted community leaders. One of the greatest shortcomings of groundwater governance has been the failure to grasp the importance of its human dimension—that is, stakeholders' goals, incentives, rights, practices, constraints, and need for trusted leaders. Building trust requires a common understanding of the problem and an accurate assessment of the proposed solutions. Such trust exists in Nebraska and Kansas, where some water districts are managed by a board of directors comprised primarily of farmers. When water users in these districts are caught tampering with well meters, they can lose their water rights, a penalty that can amount to several million dollars and that is enforced by a board of farmers (and potentially friends and neighbors). A lot of good governance is non-regulatory in terms of the effort spent to build trust and relationships within the community, whether by working with elementary school programs, outreach programs, or peer-to-peer programs. Trust building can be incredibly difficult, but that effort is critical to building successful programs.

MEASURING PERFORMANCE: THE METERING CHALLENGE

How do we know which regulatory policy experiments are successful without measuring performance? The paradigm for measuring the success of institutional programs is a checklist of whether institutional procedures were followed. However, this paradigm needs to shift to focus on outcomes and metrics for measuring achievement of goals. This new paradigm would include funding dedicated to long-term monitoring and adaptive management, because you cannot manage what you don't measure.

We have difficulty managing and regulating groundwater in large part because so few wells within any given aquifer are consistently metered and metered at a meaningful temporal resolution. Only 25 percent of groundwater wells in the United States are metered in any way, and far fewer are metered on a regular basis. Thus, the most basic (and low-cost) mechanism for measuring groundwater, and the effectiveness of groundwater management at the local to regional scale, is rarely in place.

Metering comes with baggage because it has historically been used as a regulatory mechanism, particularly in the agricultural and utility sectors. Collecting water data of any kind remains problematic for regulated entities because it is typically viewed as the precursor to increased regulation; therefore, these entities resist metering as a means of delaying potential future regulation or of undermining the information needed to justify regulations.

Overcoming trust barriers is a significant challenge. One beginning point may be articulating the value proposition of metering and demonstrating good uses of data. If the 15 million private wells in the United States were monitored, temporal and spatial water use data could be produced either for the well owner or for the local region (e.g., a group of well users in a rural neighborhood or a group of farms)—and that data could result in both water and cost savings. Private and local groups can increasingly afford to monitor their wells as sensor technology has improved and become increasingly cheap. Integration of the resulting data could indicate the onset of a groundwater problem, allowing the issue to be rapidly addressed. Demonstrating how metering and data sharing can improve the bottom line of agriculture and industry alike is imperative. For example, Coca-Cola works with NGOs to identify projects to improve groundwater recharge in the Sierra Nevada. Each entity wants to conserve water, but for different reasons: the agricultural community needs water for its livelihood, NGOs want to save water for the environment, and corporations want to ensure water is available for plant locations.

Working together toward the common goal of ensuring water availability both now and the future is incentivizing collaborative relationships. Clearly, the value proposition of sharing and integrating groundwater (i.e., well) data is even greater when used to enable and inform holistic management of water resources at broad scales.

Moving toward aggregated metering data provides opportunities to better understand the system and address problems while they are still manageable. One mechanism for such trust-based data aggregation is the National Groundwater Monitoring Network Council, which creates trust by leaving all of the data in the hands of data producers. In addition, the network encourages voluntary participation so that different organizations can make their data available and known, thus increasing the data and insights from them. Wellntel provides groundwater information systems for homeowners, small farms, and communities (those with the least resources) by developing cheap sensors that upload data directly to the cloud, and it allows clients to choose whether they would like to keep their data private or make it publicly available. Regardless of approach, increasing the number of monitored groundwater wells and integrating data—from large municipal wells to individual domestic wells to industrial wells—could increase the prospects for groundwater sustainability in the United States.

CRISIS-DRIVEN COLLABORATIVE NON-REGULATORY CHANGES: OKLAHOMA CASE STUDY

Oklahoma is a large oil- and gas-producing state. In 2014, Oklahoma injected 6.3 billion gallons (184,000 AF) of water into underground injection control wells. The large volumes of produced water has made Oklahoma seismically active; the state experienced more than 900 earthquakes of a magnitude of 3.0 and greater in 2015 alone. Coincidentally, as seismicity increased, so did drought conditions. Thus, there were limited disposal options for produced water at the same time that water restrictions were established. Growing concern about earthquakes and drought made regulatory changes possible for groundwater. State agencies, NGOs, environmental advocates, academia, and the oil and gas sector sought shared solutions, with growing enthusiasm as trust was built. This collaborative effort included equipping regulators, funding researchers to understand earthquakes and production activities, and developing policies that encouraged energy production in tangent with environmental stewardship. Two years later, the number of recorded earthquakes dropped to 620; in 2017, the anticipated number of earthquakes is 250. From this successful collaboration, a new organic collaboration formed to investigate the use of produced water as a means of improving resilience during drought, while also helping the state to meet its goal of reduced water consumption. Neither of these goals could be met through conservation alone, and both will require the use of nontraditional water sources. The relationships built during the earthquake turned what was perceived as merely an oil and gas problem into a state water problem. A state water problem involves everyone in every sector.

Options under discussion include (1) recycling produced water in the oil and gas sector, thereby reducing freshwater use; (2) transferring produced water among oil and gas plays, redistributing supply with demand; and (3) instituting fit-for-purpose water use.

Both collaborative processes focused on getting the right leaders in the different communities together in one room. No regulatory, financial, or tax incentives were directly involved in forming these groups. Oil and gas companies in Texas have taken note of the seismicity problems in Oklahoma and are seeking to collaborate with state regulators and private entities to find alternative strategies for managing produced wastewater.

IMPENDING CRISIS-DRIVEN REGULATORY CHANGE: FLORIDA CASE STUDY

The Florida Water Resource Act of 1972 created five water management districts responsible for overseeing water management plans that include the consumptive use of water, aquifer recharge, well construction, and surface water management. This process takes a long time, but 45 years later, Florida is on the cutting edge of having a diverse water supply portfolio that includes surface water, groundwater, reclaimed water, aquifer recharge, and desalination. Nearly 80 percent of water is reserved for the environment, 10 percent for industry, and the remaining 10 percent is shared by public supply and agriculture. Although public supply has recently outgrown agriculture, nearly half of that supply is used for irrigation of lawns and turf (e.g., golf courses).

Florida engages in water supply planning over a 20-year horizon, and it updates water supply plans every 5 years. Each district had a different understanding of the Floridan aquifer system because each district has different plans and uses different data and models that all show different impacts under future withdrawal scenarios. The lack of a common framework and understanding of the system led to disputes until the governor organized the Central Florida Coordination area and requested collaboration of three water management districts (Suwannee River, St. Johns River, and Southwest Florida) to develop a regional water supply plan. This collaborative effort as also included the Florida Chamber of Commerce, agriculture, and the Sierra Club. Most participants were initially reluctant to work together, but over time they began sharing data in order to move toward a shared understanding of the underlying Floridan aquifer system.

The common goal was to decrease freshwater use (currently over-allocated by ~200 MGD) and to move to use of brackish water and ocean water and to potable reuse. The water utilities in the region had significant incentives to work together given that they would be affected by the over-allocated water resources. Permits with 10-year windows provided another incentive for collaboration to mitigate impacts and ensure adequate water supply during permit renewal. This combination of a common vision and an impending regulatory hurdle created the necessary impetus for regulatory change.

CRISIS-PRODUCED REGULATORY CHANGE: SUSTAINABLE GROUNDWATER MANAGEMENT ACT, CALIFORNIA

California was one of the last states to regulate groundwater, and like many states, drought was the driving force. During the drought, surface water allocations were reduced, and water users replaced the missing surface water with groundwater extracted from aquifers (increasing the relative contribution of groundwater from 40 percent to 60 percent), causing groundwater levels to plummet.

The Sustainable Groundwater Management Act (SGMA), passed in 2014, established goals and values on which most everyone could agree—namely, to use groundwater wisely and to avoid negative consequences such as subsidence, low groundwater levels, saltwater intrusions, and degraded water quality. Like many states, California devolved responsibility to local entities; the SGMA gives authority to 127 local groundwater basins to determine existing negative consequences and to develop their own solution sets to move toward sustainable groundwater development. Ideally, each basin will also establish positive goals that complement avoidance of negative outcomes—for example, assurances that groundwater owners' rights have become more secure. Each Groundwater Sustainability Agency (GSA) will need to initiate a collaborative process to determine the problem and solution sets for its particular groundwater basin. The solution sets can be created from scratch or adopted from other places, including Israel and Singapore, both of which have developed innovative water technologies and irrigation practices. The primary challenge is to determine how to tailor adopted solution sets to fit within the context of the authorities and agencies within California.

The development of SGMA is one that many states and water management districts are watching because the various GSAs will be implementing a wide variety of approaches and practices. Deployment of this vast regulatory approach is making California a laboratory for water governance.

CURRENT MARKET OPPORTUNITIES IN GROUNDWATER

Groundwater markets have attracted much attention as a potential solution to curbing groundwater depletion. Water markets often rely on water banking, or the storage of water, for later access. Aquifers provide a natural storage container for trading within the specific region of the aquifer, or if infrastructure exists, into a much broader region. Groundwater storage is more efficient than surface water storage as water is not lost to evaporation with either public or private investment in infrastructure (wells) providing access to the water. Thus, aquifers provide a natural water bank for market development and trading.

Markets can be a powerful tool; and when conceived and operated appropriately, they can achieve efficient outcomes that include economic benefits and environmental conservation. However, if poorly designed or executed they can create perverse incentives and significant resource damage. Some of the primary outcomes achieved from well-functioning markets include increased water efficiency, conservation, reduced conflict, and better appreciation for the value of water.

Prior to exploring the opportunities for groundwater markets, it is important to address a plethora of misconceptions held by regulators, practitioners, water managers, and the public:

- **Water markets are new.** The oldest documented water trading occurred 1,000 years ago. In the United States, water markets consisting of informal, bilateral transactions between willing buyers and sellers are abundant. While there may not be commodity-like trading floors or groundwater-based secondary markets, there are active and valid water markets.

- **Water markets must include metering water volumes.** Water markets can be built around proxy indicators such as the right to irrigate land, well permits, power usage, and timing of use. That said, in the long-run, metering is critical to groundwater management and are a goal for water markets to move toward.

- **Water markets only work with certain water allocation rights.** Water markets can work with all kinds of water and property rights from the High Plains in Texas (Rule of Capture), to Nebraska (Correlative Rights), to China (few water rights present). Water markets can exist based on number of irrigated acres, substituting well defined land rights for undefined water rights.

- **Water markets are *the* solution.** Water markets are not the solution, but are part of a portfolio of solutions. Using water markets to mitigate environmental impacts may not work in all aquifers because aquifer recovery times may exceed the patience of market participants. Domestic wells are also likely to have limited capacity to participate in markets.

- **Most water markets are formal markets.** While most research is based on formal markets, many water markets are informal. Informal water market users often don't self-identify as participating in a water market just as someone selling a used car does not self-identify as participating in the auto industry market.

- **The regulatory and financial components of a water market should be bundled together.** Water markets have a regulatory component that reduces uncertainty and provides price discovery and information sharing. They also have a financial component that addresses the transaction of money between buyer and seller. These two components can be, and perhaps ought to be, handled separately.

- **Agricultural communities will not benefit from markets.** Improvements in water technology and irrigation management use less water to produce higher quality crops at a higher yield, leaving surplus water for the agricultural community to sell to other users. San Antonio, Texas is dependent on water from the Edwards Aquifer, which has capped withdrawal rates due to endangered species. The growth of the city was made possible because water and irrigation management allowed growers to conserve water while producing more food and selling the excess water to San Antonio.

There are many challenges to developing and implementing a successful groundwater market. First, much of the infrastructure is privately held and precludes the ability of federal or state agencies to provide an economic impetus through infrastructure to drive groundwater markets. Second, groundwater is hydrologically complex, particularly in areas with significant surface water where groundwater interactions can influence the outcomes of similarly structured markets. For example, in Nebraska two similarly structured markets had opposite outcomes primarily due to subtleties in hydrologic processes. Third, formally structured groundwater markets can have high transaction costs that impedes simple transactions. Fourth, much of the water that is conserved as part of a transaction is typically for downstream benefits, or is used by another sector (e.g., rural-to-urban transfer of water). Finally, building water markets in areas that have little initial groundwater governance presents potential long-term risk as a poorly implemented water market in the past may inhibit the adoption of water markets in the future once groundwater governance is developed.

USING WATER MARKETS FOR INSTREAM FLOWS

The four primary ways to protect instream flows are (1) state restrictions and regulations that limit withdrawals and/or require mitigation; (2) the Endangered Species Act (ESA) can result in water rights being denied or diminished; (3) appropriate water for instream purposes; and (4) acquiring existing water rights to leave water instream.[6] Markets can provide an entry mechanism for new water users, such as the environment, in western states where water supply has been fully allocated. From 2003 to 2012, approximately 40 percent of formal water transactions were for environmental purposes, accounting for 7 percent of the total cost of water transactions during the same period.[7]

Environmental advocates are interested in developing water markets to obtain water that is kept in stream for conservation and environmental benefits. The Bureau of Reclamation acquires 427,000 AF per year through one-year leases of uncontracted water stored in reservoirs along the Snake River, Idaho to augment flows to protect endangered fish populations. California purchases water for instream flows through large scale water deals that are backed by federal and state programs.[8] The Platte River Recovery Implementation Program uses water markets to idle irrigation and enhance Platte River flows.by capping the number of irrigated acres and enabling farmers to exchange certified irrigation acres on a year-to-year basis. This solution increases water availability for instream flows on a temporary, year-by-year basis without permanently drying up acres. The exchange is administered by a third party that matches buyers and sellers, based on bid parameters and location, to ensure transactions will be beneficial to streamflow.[9]

Cap-and-trade programs are ideal for depleted aquifers. Regulatory agencies set a maximum cap on water withdrawal or aquifer levels and only allow trading to occur under that cap. Water rights can be purchased from active users and then retired through permanent conservation or by leasing the rights for conservation over a set time period. For example, the Upper Republican Basin in Nebraska and western Kansas set an annual water right for irrigators that are converted into 5-year

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[6] Scarborough, B. (2010). Protecting Steam Flows. In R. Meiners (Ed.), *Environmental water markets: Restoring streams through trade* (pp. 9-12).

[7] WestWater Research. (2014). Environmental Water Markets. *Water Market Insider, Q4.*

[8] Ibid.

[9] Ruan, A. (2016, March 7). Groundwater exchange to help irrigators help each other. *Hastings Tribune.*

allocations. This creates flexibility for when irrigators use or trade their water rights with other farmers within a 5-year period.

Caps may extend to other markets to incentivize groundwater recharge. For example, credits could be earned when stormwater or wastewater are used to recharge an aquifer rather than flushed downstream. Surface and groundwater markets might coincide to address climatic variability, shifting the emphasis on surface water during wet conditions and groundwater during dry conditions. A joint trading program could produce credits for surface water that are used to recharge groundwater and those credits could be traded during drought when groundwater demand grows.

MARKETS AND METERING

While not required for markets, long-term metering will likely be necessary to ensure that market participants are complying with transactions and that benefits, such as aquifer recovery, are being accrued from the market. Surface water is more readily monitored through publicly-owned infrastructure or stream gauges, whereas groundwater is located under private property and requires the construction of wells to monitor water depths. This creates unique challenges to deploying monitoring technology and managing groundwater resources across a wide region.

Substitute metrics are needed until groundwater monitoring becomes more prevalent. Every drop of water pumped requires electricity, which has a robust market and might serve as a better mechanism for groundwater markets than metered water. California agricultural providers were compensated to adjust water schedules to avoid pumping groundwater during peak energy demand with electricity usage providing the compliance mechanism. Electricity is also required for water treatment, with brackish and desalination having the highest costs. Developing a water market to trade different levels of water quality that are fit-for-purpose based on energy costs might create a more robust market in the short-term until meters and water treatment costs are easier to obtain.

The sheer quantity of privately owned wells presents another metering challenge. One basin in California has 40,000 wells; creating enormous opportunities for transactions through a thick market (see Metering in California) but huge challenges in terms of expense. Good quality meters cost between $800 and $3,000 per well, which sets an entry-level barrier to metering and a desire to use surrogate metrics (such as satellite technology or electricity usage).

METERING AND MARKETS IN CALIFORNIA

SGMA presents an opportunity to establish groundwater trading to facilitate water conservation by converting from high to low water crops. The creation of a robust, formal groundwater trading market is hamstring by inadequate data. Groundwater data in California is negligible, meaning decisions and transactions will have to be made with high uncertainty. However, many irrigation districts and farmers are hesitant to allow metering and monitoring of their wells that have historically led to regulations. For example, in Kern County, monitoring revealed an over-drafted aquifer that resulted in no new well permits for farmers while urban development and growth were allowed to drill new wells. Data are needed to manage groundwater resources and facilitate formal trading markets; however, how can the mistrust and historic harms be addressed to enable data collection and use? Moving toward an Internet of Water – an interoperable network of interconnected data producers, hubs, and users that will enable connecting and transmitting water-related data and information in real-time[b] – may provide trusted, neutral 3rd party brokers who can aggregate and anonymize data for use while protecting individual communities from the threat of regulatory oversight.

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[b] The Aspen Institute. (2017). *Internet of water: Sharing and integrating data for sustainability - A report from the Aspen Institute Dialogue Series on Water Data.* Washington, DC: Patterson, L., Doyle, M., and Monsma, D.

MARKET LIMITATIONS

Markets create significant opportunities, but they also have challenges and limitations. For instance, not everyone has access, or the ability, to influence market design, and thus markets produce winners and losers. Those who have significant financial resources and limited water demand are the most likely to benefit from functioning water markets because the price of water is a small fraction of their total operational costs. Current water users stand to benefit from markets by allowing them to use their water rights for short-term or long-term revenue generation through leases and sales. Those without resources, including the environment, may be priced out of the water market. Groundwater-dependent communities and agriculture could be adversely impacted if significant transactions remove water from their region.

A well-functioning market has three primary characteristics: transparency, liquidity and consistency. None of these characteristics are predominantly present in groundwater. Transparency requires having access to data and sharing the data among all market participants; groundwater is extremely non-transparent due to lack of monitoring data coupled with the inability to directly observe groundwater.

Liquidity means transactions can be made readily between buyers and sellers; however, there are regulatory, infrastructure and transparency barriers for buying and selling groundwater. For example, transferring water volumes between uses carries a lot of complexity with water rights, like rezoning and repurposing properties. One regulatory barrier that needs to be addressed is the "no injury" clause; whereby transactions have to prove the transaction will not cause harm to other downstream users. Consistency means the rules of the market can scale, allowing the initially high transaction costs to rapidly decline as future transactions occur. However, there is little consistency between aquifer characteristics and regulations, meaning that it is very difficult to translate a transaction between regions.

Groundwater markets face significant challenges, but because they are nascent and have a less developed regulatory framework, there are opportunities for co-developing markets and regulations to support one another. For example, in Nevada there is a pilot program in Diamond Valley to temporarily alter the regulatory framework to create a cap and trade program where shares are allocated each year depending on groundwater availability.[10]

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[10] Young, M. (2015). *Unbundling water rights: A blueprint for development of robust water allocation systems in the western United States.*

USING TECHNOLOGY AND SCIENCE

The role of science and technology in water resources management is rapidly evolving, from observations and data to treatment and disposal technologies. Groundwater has been monitored and managed on an ad-hoc basis, which has precluded broader understandings and management strategies for sustainable development. However, underlying all modeling and management efforts are data collected through these relatively sparse monitoring networks. Publicly available groundwater data has limited spatial and temporal resolution that are often inadequate for many industrial and agricultural decision-making needs, such as site location and managing supply chain risk. Monitoring networks need to be further resourced and expanded; however, the purpose for investing in data collection must be linked to the insights that data can provide to inform decision-making, such as site location, investment opportunities, and watershed management strategies. All data and technology must be fit-for-purpose to obtain any substantial level of funding and adoption. There must be collaboration between innovators, users, and regulators.

The purpose for investing in data collection must be linked to the insights that data can provide to inform decision-making, such as site location, investment opportunities, and watershed management strategies.

Water quantity and quality form the base of every water-related problem. Technology can contribute to addressing water quality problems and open up new sources of brackish or saline water that were previously too cost prohibitive to treat. However, technology cannot manufacture additional water to solve the quantity problem. Currently the only way to estimate groundwater quantity is through models that require understanding geology, porosity, boundaries, streamflow depletion, recharge, stream capture, etc. Collecting the baseline data requires funding, which has replaced science and technology as the limiting factor to understanding groundwater quantity. While data are not the solution, data plays a key role in modeling and decision-making, as well as in education, messaging, and markets.

ADVANCEMENTS IN GROUNDWATER DATA

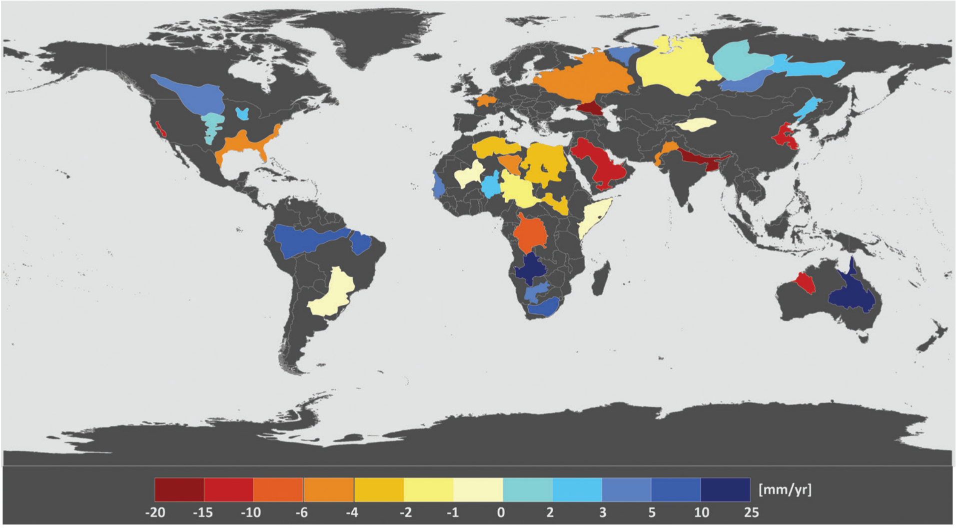
In the United States, the USGS monitors and disseminates surface water and groundwater data through the National Water Information System (NWIS). The USGS has 877,845 wells with at least one water depth observation, and 300,000 wells with at least one water quality observation. There are 16,410 active groundwater wells measured at least once in the past 13 months, of which 1,133 wells are measured daily and 1,643 wells are measured in real-time.

The USGS has also contributed in the development and implementation of the national groundwater monitoring network (NGWMN) to help address the major data gaps for managing groundwater resources. NGWMN pulls data from federal, state and local groundwater monitoring networks into a single portal. The NGWMN has 6,743 active wells (5,724 water level and 1,315 water quality) between 19 contributing agencies and 52 states as of March 10, 2017. Participation in the groundwater portal is voluntary and allows data producers to maintain control over the data. The data are pulled into the portal in a standardized format to facilitate data sharing in real-time based on user query. Funding for this program took 10 years to obtain and is part of the federal budget.

In addition to well-based approaches, satellite and remote sensing are increasingly used to understand how groundwater volume is changing over large areas. NASA's Gravity Recovery and Climate Experiment (GRACE) launched in 2002 is the only satellite that explicitly measures changes in the water column by measuring changes in mass each month. GRACE does not distinguish between snow, surface water, soil moisture or groundwater; relying on the use of other data to determine which fraction relates to changes in groundwater. GRACE has enabled large scale understanding of changing water budgets (Figure 2).

Remote sensing data provides another avenue to assessing groundwater changes at 30 to 120 m spatial resolutions every 16 days since 1982. The value of these data are in the composite image: vegetation index, land surface temperature, and a normalized difference water index. The Climate Engine Application (http://climateengine.org/) provides on-demand cloud computing and visualization on this remotely sensed data. The Climate Engine comes from a partnership between the University of Idaho, the Desert Research Institute and Google. The application has been used to assess the impacts of groundwater pumping on vegetation.

Figure 2: GRACE Groundwater Storage Trends from 2003-2013[11]



INCORPORATING PRIVATE DATA - AGRICULTURE

Global population is expected to grow by 50 percent over the next few decades, placing enormous pressure on the agricultural community to find more efficient, sustainable ways to grow significantly more food. Digital agricultural companies are working to transform a wide variety of data into information that supports agronomic decision-making for each acre of farmland. The underlying business model is using data to uncover inefficiencies and help growers to discover new solutions that will result in large production gains. Farmers are willing to provide their data because there are clear ground rules established: farmers own their data, the digital company will not share the data, and they can only help the farmer to use that data to improve management practices. An individual farmer only has 30 to 40 tries in a lifetime to improve crop growth, and data can help improve his or her practices rapidly. The last five years has seen remarkable transformation from little data sharing to farmers sharing seed, fertilizer and yield data as they directly experience the value of sharing their data. The value proposition for sharing their data with others, even in an aggregated form, is not immediately obvious. Building trust starts slowly and over time farmers will start to see some of the benefits of sharing derived data. In the future, farmers may be willing to share their data in an anonymized, aggregated fashion as agricultural infrastructure changes and data sharing becomes more culturally acceptable.

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[11] Richey et. al. (2015). Quantifying Renewable Groundwater Stress with GRACE. *Water Resources Research.* For aquifer and basin names see: https://www.jpl.nasa.gov/images/earth/grace/20150616/grace20150616.jpg

Groundwater data are not easily integrated and shared between platforms; however, sharing and integrating public with private data provides tremendous opportunities: water rights could become more secure, communities can be meaningfully engaged, state agencies could become data service providers, improved trust, optimized water systems, greater resiliency, and sustainable development that allows economic development, protects drinking water, and improves ecosystem health. However, until a business case is made for sharing and integrating data, there is likely to be minimal investment to create these platforms. Regulations and policies tend to focus on the process and not the outcomes, leaving monitoring and data as an afterthought. Including data collection and sharing into institutions and policies will only occur if funding mechanisms are in place to support these efforts over the long-term as part of the daily operation of an organization and not a one-time project. Collaboration between science, technology, investors, stakeholders and policy makers will be needed to create seamless and transparent data sharing systems that can provide a common platform and understanding of the system shared by stakeholders.

ADVANCEMENTS & OPPORTUNITIES IN SENSORS

Recent developments in water technology are drastically reducing the costs of data collection. There are an estimated 3.5 million oil and gas wells that have been drilled in North America[12], 476,000 irrigation wells, and 96,900 domestic wells.[13] Private wells represent an enormous potential to expand the spatial and temporal resolution of groundwater monitoring. Until recently, groundwater monitoring required relatively expensive equipment and professionals to obtain and understand the data, leaving private individuals ignorant of groundwater conditions and unable to meaningfully engage with groundwater issues.

Technological advancements produce cheaper sensors and meters that provide access to private citizens. Wellntel provides relatively inexpensive meters (between $800 and $1,200) that track groundwater levels (supply) and pumping (use). One of the key aspects of Wellntel's approach is that the data are not only collected, but also handled for the user: the data are transmitted directly to the cloud where private citizens can view their data. The customer maintains the choice of whether, and with whom, to share the data. Community networks may choose to aggregate well data (while masking the identity of individual wells) to get a better picture of the underlying groundwater system. This approach provides a balance between the need for data and the protection of privacy.

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[12] Resources for the Future. (2016). *Plugging the gaps in inactive well policy.* Washington, DC: Ho, J., Krupnick, A., McLaughlin, K., Munnings, C., and Shih, J.

[13] NGWA. (2017). Groundwater use in the United States of America.

The majority of Wellntel customers are communities establishing groundwater monitoring networks to understand their groundwater condition. For example, a farming community in Wisconsin wanted to establish a groundwater baseline prior to the arrival of a concentrated animal feeding operation. The State of New Mexico distributed sensors in areas of the state with little groundwater data available. Allowing private citizens the ability to understand and engage with their water systems, particularly as a community, is empowering, promotes data sharing and innovation, and builds trust through increased transparency. Similarly, water quality sensors could be installed in the well, which would also address public health concerns for the many domestic wells that aren't monitored regularly for water quality.

ADVANCEMENTS IN WATER TREATMENT TECHNOLOGY

Advancements in water treatment technology have the potential to benefit multiple sectors through improved water efficiencies by addressing issues around aging infrastructure, sustainable development, and smart water.

One significant challenge for water treatment technology is that many water users, particularly utilities, are risk adverse and reluctant to be early adopters of new technologies. However, negative consequences (degraded water quality, lower groundwater levels, saltwater intrusions, and so on) resulting from unsustainable groundwater pumping, increasing demand, regulatory changes, and more extreme events under a warming climate are forcing utilities to adopt innovation out of necessity. For example, Florida set a goal for no wastewater to be discharged to the ocean by 2025. Meeting such an ambitious goal has necessitated innovative business models that include different treatment technologies to make water fit-for-purpose in terms of quality; thereby, freeing up more freshwater resources while reducing treatment costs for purposes that don't require potable water. Moving toward a fit-for-purpose treatment model requires legislative changes and developing legal definitions around what constitutes "fit" for specific purposes, i.e. thresholds and benchmarks for potable water quality.

Adopting new technology often goes in hand with adopting new business models. Public Private Partnerships (P3s) can facilitate the adoption of new business models (see Public Private Partnership in Arkansas) and generating innovations that aid utilities as they seek to address increased regulations, implement conservation and efficiency programs, and adjust to reduced public funding. There is a huge business opportunity and utilities are being inundated with offers of new technologies; requiring utilities to either ignore new technologies or invest in assessing how that new technology meets their needs. Most utilities cannot afford the risk of new, unproven technologies which may not generate the savings suggested, or do not meet regulatory needs. A third party, such as a private or NGO entity, that streamlined and vetted the plethora of technologies would be advantageous. This third-party entity could also identify gaps and needs for new technology as part of a two-way conversation between utilities and technology companies, essentially ensuring that the technologies are meeting a specific need. In addition, the adoption of new technologies costs the utility time and money to train staff. The upfront costs of adopting new technologies may be reduced through shared knowledge across the utility sector.

Industry also faces risks as earlier adopters of new technologies because water is linked to public health. Water-related emerging technologies bear higher risk because there is a direct link to human health outcomes and must be proven prior to adoption. Thus, water technology companies are required to make long-term investments in new technologies that might not ever make market.

PUBLIC PRIVATE PARTNERSHIP IN ARKANSAS

In 1996, the Arkansas Natural Resources Commission established the State's first Critical Groundwater Area (CGA) composed of 5 contiguous counties, including Union County. CGA criteria requires (1) groundwater levels declining at a rate of 1 foot or more per year, (2) ground levels are at or below the top of the Sparta aquifer, and (3) groundwater quality is threatened. Union County relies solely on the Sparta aquifer for municipal and industrial use and was pumping groundwater at unsustainable rates that led to declines of 7 feet or more per year. Stakeholders recognized that high groundwater pumping threatened the region's economic development. Stakeholders worked with the United States Geological Survey (USGS), who had the data and could do the modeling to answer questions around (1) how much water was being used, (2) how much water could be used (sustainable or safe yield), and (3) how long could Union County continue pumping at these rates without inflicting irreparable damage on the Sparta aquifer? Subsequent USGS models indicated that if Union County did not reduce consumption by 72 percent within 5 years or less there would be irreparable damage. By 2005, a combination of public and private funding enabled Union County to finance a $65 million infrastructure project to provide an alternative surface water source for the major industries reliant on groundwater. Groundwater levels have since risen dramatically, up to 90 feet in some areas. Collaboration is a key component of solving the sustained depletion of groundwater; however these collaborations are facilitated by having a common picture of historic and current conditions (a common platform of data and models) as well as public policy and financing mechanisms to implement agreed upon solutions.

AQUIFER STORAGE AND RECOVERY

Aquifer Storage and Recovery (ASR) is increasingly being incorporated in groundwater management plans. ASR pumps water into a suitable aquifer during times when water is available (i.e. winter months or wet years) and recovers the water for use later when it is needed (i.e. high demand in summer or drought), essentially using the aquifer as a storage reservoir. ASR wells are regulated as part of the UIC Program. Injected water can include surface water, treated drinking water, and treated wastewater or stormwater, depending on the needs of the managing area and formation of the aquifer. Further technological developments are needed to ensure that different water types injected does not compromise the aquifer's water quality. The EPA estimates that 89 percent of documented aquifer recharge and ASR wells are located in ten states: California, Colorado, Florida, Idaho, Nevada, Oklahoma, Oregon, South Carolina, Texas and Washington.[14] ASR performance is typically defined as efficiency, with a perfectly efficient ASR system able to recover the same amount of water stored. Estimates for recovery capacities range from 0.5 to 8.0 million gallons per day depending on the characteristics of the aquifer.[15] Recharge estimates are challenging to model with more research needed

ASR assist in preventing or reversing the environmental consequences of saltwater intrusion and land subsidence, as well as providing resiliency to the system for later reuse. Recharging a depleted aquifer could also provide summer time flows to streams that were previously dry.[16] The underground storage system requires little land use, reduces concerns over levee failure and downstream flooding, and allows water sources to be closer to urban areas. The potential disadvantages of ASR include the high cost of the project in relation to the potential low recharge, recovery rates are lower than surface storage, and inadvertently creating water quality issues.[17,18]

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[14] EPA. (2016). Aquifer recharge and aquifer storage and recovery. Washington, DC.

[15] Pyne, D. (2014). Attenuation of disinfection by products during ASR storage. *Southwest Hydrology.*

[16] State of Oregon Department of Environmental Quality. (2014). Fact Sheet: Aquifer storage & recovery and artificial groundwater recharge. Portland, OR.

[17] USACE. (1999). Central and southern Florida project comprehensive review study: Final integrated feasibility report and programmatic environmental impact statement. Jacksonville, FL.

[18] Bloetscher, F. and Muniz, A. (ND) Aquifer storage and recovery: Issues for south Florida's long-term water supplies.

WHAT ARE THE BIG OPPORTUNITIES?

Groundwater has been largely ignored until problems become visible or the functionality of the services aquifers provide are reduced. Proactive, collaborative interventions supported by data and technology can preserve more of the functionality and benefits that groundwater provides. A proactive approach establishes desired goals for groundwater, such as ensuring shallow access by domestic wells and the continued flow of groundwater dependent streams. The goals need to be measurable and based on a common understanding of groundwater provided by shared data. The path to intervention will vary between locations based on the specific groundwater management goals set forth by stakeholders.

Co-produced interventions through collaborative partnerships was repeatedly highlighted as necessary to engage communities and find innovative solutions. However, many industries and communities are struggling to locate these opportunities. Industry wants to be a part of the solution but finding a risk acceptable problem within their mission statement is challenging. Conversely, poor, rural communities are often excluded from these collaborative opportunities. Mechanism are needed to connect industries with potential solutions and funds to communities with specific problems and needs. Peer-to-peer learning networks provide one means to match entry level players with those who have been well-established in groundwater efforts.

One challenge is that tools, best practices, and success stories around solving groundwater programs tend to remain local. Intentional efforts to create a menu of groundwater problems and successful interventions would be a tremendous resource to help accelerate future collaborative intervention efforts. Additionally, a WebMD version for groundwater could matches symptoms to potential problems, next steps to confirm the diagnosis, and finally potential solutions or next steps forward. This type of tool would facilitate the sharing of success stories from different localities.

COLLABORATIONS: ONE WATER FOR ONE COMMUNITY AND INCENTIVIZING CHANGE

Groundwater is a common resource and its solutions will require collaboration within communities and across regions and sectors. It is imperative to ensure regional solutions include not just groundwater stakeholders, but surface water, reclaimed water, brackish water, and other regional water supply considerations. An integrative water resource management plan can holistically address water quantity and quality problems while providing additional opportunities for expanding conservation, market, and water fund opportunities. While motivations vary, there are often common co-benefits that can be found between different stakeholders whether they are environmental, societal, or economic (see Peru Collaborative Co-Benefits).

PERU COLLABORATIVE CO-BENEFITS

Freeport-McMoRan has a mine in Peru near a city that dumped raw sewage into the Rio Chile. Downstream agricultural farmers were restricted by the government from selling their products because people were getting sick. Freeport-McMoRan constructed a wastewater facility for this city that produced multiple co-benefits. Freeport-McMoRan reduced their groundwater footprint by reusing wastewater from the facility, the city benefited by having a wastewater treatment plant, the environment benefited from a cleaner river, and the agricultural sector benefited from lifted restrictions to sell their food products. This collaborative project between a mining industry, downstream agricultural farmers, and a municipality found a creative solution that met each sector's needs and produced additional environmental co-benefits.

"Golden triangle projects" are projects between government, civil society, and corporate businesses that produce win-win situations. For example, the Rio Grande Water Fund is a collaborative partnership among more than 40 organizations to address both water quantity and quality problems in the Rio Grande caused by wildfires. The water fund is designed to treat 600,000 acres over a 20-year period. Another example is a partnership between The Nature Conservancy, the Georgia Flint River Soil and Water Conservation District, and farmers to reduce pumping from the Floridan Aquifer to improve baseflow in Flint River. The project uses data and technology to prioritize irrigation infrastructure upgrades to conserve water. Partnerships also include smart city efforts where stakeholders cab collaborate in places like university and industry labs (UI Labs) to solve specific problems within their city.

Collaborative interventions have the opportunity to raise awareness because there are many voices involved in groundwater decision-making. Corporate America could have a large voice in raising awareness with its customer base, as well as influencing on-the-ground efforts through their supply chain. It is imperative the message corporate America sends to its supply chain is that it is good to use less water to make the same amount of a product.

Drivers for these types of collaborations are either crises or incentives, with incentives being preferable. The best advocates for incentivizing change are those within a community who benefit from new collaborations. Bottom-up collaborations provides greater flexibility in decision-making, and enables individuals to take responsibility for calculated risk. For example, supplying tools that give farmers the freedom to assess what grows best given certain field conditions and water needs empowers the individual to make informed decisions on crop choices. While crisis and regulatory change can be great drivers for sustainable development; the process is often slow and subject to reversal once the crisis has passed or regulations have changed.

For utilities, economics are often an incentivizing issue. Groundwater provides the least expensive means to provide water to their customers. Effective communication highlights that inefficient groundwater use is giving away the utilities' best asset with far higher costs paid to obtain water from elsewhere.

INSTITUTIONALIZING COLLABORATIONS TO ESTABLISH LONGEVITY

Organic collaborative efforts can work quickly and efficiently; however, there needs to be some regulatory structure established to ensure the longevity of these efforts. Regulatory structures can also reduce investment risks and provide access to additional funds. Many successful collaborations occur because of the leadership of a few key people; however, institutionalizing the relationships can allow collaborations to survive personnel changes. Collaborative efforts require dedicated funding streams that should be a part of the institutionalization.

While regulations are unpopular, they provide the authority, and facilitate action, for local decisions to be made and implemented. States are placed in a goldilocks situation of determining whether new regulations are too strict and punitive, too weak and ineffective, or just right. The challenge when establishing regulatory structures is to find the sweet spot that produces change while allowing for flexibility in the process. The downside of institutionalizing collaborations is that these agencies tend to be slow adopters in terms of technological changes and new innovative practices that enable goldilocks flexibility.

EDUCATION AND COMMUNICATION

Surface water can be directly seen, touched and experienced. It is something humans can connect with and understand. However, groundwater cannot be seen or directly experienced and what is out of sight and out of mind typically falls to the wayside. Similar to well-functioning utilities where high-quality water is always delivered, the public comes to always expect water to be available and they take it for granted. Groundwater and utilities only become visible to the public when there is a problem, such as land subsidence, wells running dry, water line breaks, and boil alerts. Many rural, domestic communities, estimated 1.8 million people in the U.S. today that do not have access to running water, are already suffering from groundwater problems but don't have the information, resources, and/or understanding of these systems to effectively engage these problems. Little public education and investment in utilities, or groundwater, occurs prior to invisible problems becoming visible. And at that point, there are high costs and time horizons to fix the problem.

Similar to climate change, groundwater impacts are slow to become visible and are slow to remedy. Dedicated education and communication efforts around climate change over the last decade have convinced more than 50 percent of Americans that climate change is real and CO2 should be regulated. It is essential that education and communication efforts convey how today's decisions will impact groundwater in the coming decades. Scenario planning might be an ideal communication tool linking individual choices to tangible outcomes, which is an essential step toward buy-in and collaboration to solve groundwater problems, or better yet, prevent future crises. For example, tying the cost of replacing groundwater with other water sources if groundwater availability is reduced in the future.

There is a large opportunity to educate the public and decision-makers about groundwater prior to crises. Addressing water scarcity, and groundwater in particular, will be a slow process. Groundwater can be made visible through maps, models, and interactive tools that enable exploration and are linked to a community's experience. Analogies that are simple to understand can be a helpful tool to get conversations started.

MESSAGING

There are five key components to effectively communicate groundwater issues to the public that must be stylized by water sector or geographic location. First, the problem and goal need to be clearly defined. This statement could be as simple as "groundwater levels are declining and we want to be good stewards of this resource by decreasing water use so the aquifer can recover." Second, provide a level of urgency highlighting the importance of addressing the issue now. Third, clearly articulate the negative impacts of groundwater depletion and link those impacts to personal experience and costs. Fourth, clearly communicate that the collective "we" are the cause – anyone who uses groundwater for anything. And perhaps most importantly, communicate that there are viable solutions and action points – steps each individual, community, or water sector can take to proactively improve the situation. Fifth, repeat this message frequently through trusted communicators within a community or sector.

Groundwater messaging should make intuitive sense to broad communities who don't think about groundwater. The messaging campaign around SGMA, for instance, had to combine the proper messages with appropriate messengers and visualizations to ensure the importance of groundwater was conveyed clearly, was relevant, and came from a trusted source to different sectors. Industrial partners can be effective at conveying the scale of the challenge. For example, Monsanto works directly with farmers (who compose approximately 25 percent of the groundwater used in the U.S.), and thus, Monsanto can be seen as a trusted messenger for groundwater to the agricultural community.

Crises can also provide windows of opportunity to communicate the realities of groundwater. For instance, the Edwards Aquifer level was reported on the weather channel (see Edwards Aquifer Water Fund) that are watched by everyone. Weather channels (or news channels) have also been used to report on earthquakes from underground injections and reservoir levels during drought. These types of approaches – having a trusted messenger deliver hourly or daily updates on groundwater (similar to weather) are necessary for long-term messaging to increase public awareness and appreciation.

A word of caution, we need to be careful on how the message is crafted to ensure surface water and groundwater remain connected and that we are talking about "One Water" as an integrated system. Slogans such as "One Water" are helpful to convey complicated ideas to the general public. If the message is not clear, the public won't understand where their water is coming from and how different water sources are interconnected. Social media could be used to engage young folks on not only groundwater, but also the integrated nature of water. Moving toward a holistic "One Water" approach will require changing regulations that hinder integrated water management.

EDWARDS AQUIFER WATER FUND

The Edwards Aquifer (EA), Texas is the primary water source for nearly 2 million people, including the city of San Antonio. The aquifer supports agricultural, industrial, and recreational activities. EA has high surface water – groundwater interactions with the aquifer sustaining ecosystems hosting endangered species. In the 1990's, the mayor of San Antonio invested in a communication campaign about the importance of the EA as the primary source of drinking water and the costs to treat the water if the EA becomes polluted. EA water levels were broadcasted on the Weather Channel and became a part of the daily news in the community. After the campaign effort, 80 percent of Texas voters approved to use public funds to establish a water fund to protect the aquifer. To date, nearly $1 billion has been raised, conserving nearly 120,000 acres of land to improve water quality. Additional co-benefits include the creation of open space, improved biodiversity and stormwater benefits. Stacking both ecological and economic benefits is an attractive proposition.

THE ROLE FOR SCIENCE

Scientists within academia and the broader research community have the potential to meet some of the research gaps around groundwater resources by participating in research that crosses boundaries between sectors and discipline, and by setting research goals that can be applied to specific problems. Researchers have at least 6 opportunities to further the mission of sustainable groundwater development.

- Universities could allow problems to drive research agendas and participate in more collaborative, applied research for clients.
- Researchers could step into the role of interventionists by providing potential solutions. Having an action point for engaging problems is empowering. For example, Arizona State University partnered with the Earth Genome Project to create a tool that compares the cost efficacy of using fallow farmland for flood recharge. These types of tools have the opportunity to be scaled across the nation and/or developed internationally.
- Currently, most data are used to show where groundwater is depleted or having a negative impact on the land surface. Academics can find ways to use data to measure success and opportunities, such as ideal locations for groundwater recharge.

- Research could show how to better bundle assets to identify opportunities that enable water conservation and economic development. For example, identifying the most beneficial use of land such that an unprofitable piece of farmland might instead be converted to a solar farm used to produce energy for the farm while conserving water that would have produced a low yield.

- Academic institutions have the capacity to form unique partnerships with both the public and private sector to find innovative solutions. These partnerships provide an opportunity to build trust and foster new collaborations in the future.

- Academic institutions are uniquely positioned to have the knowledge, capacity, and mission to create educational and communication tools on groundwater for students and the public.

CONCLUSION

The last decade has brought a dramatic shift in awareness of groundwater and our expectations for its management. Groundwater awareness has grown as problems became visible and aquifer functionality decreased. Growing awareness has coincided with technological advancements and understanding of groundwater systems that are shaping the plethora of ongoing groundwater management experiments. The stakes for learning to manage this resource are high.

Managed carefully, aquifers are a cheap natural infrastructure that could provide a stable water source for generations. However, without proper management, this natural infrastructure will deteriorate and become unusable, increasing costs of, and reliance on, almost all other aspects of our water systems. Replacing the functions of aquifers through traditional infrastructure projects, whether treatment plants or reservoirs, would come at staggering costs.

There is a lack of shared vision as to what constitutes good groundwater management and governance. The consensus at the Aspen Forum was that groundwater needs to be sustainably developed, meaning groundwater use must be balanced among economic development, environmental health, and quality-of-life needs in a way that allows our children and grandchildren to enjoy a use comparable to todays. Technological improvements are creating more opportunities than ever to pursue the sustainable development of groundwater.

Across the United States, there are many on-going regulatory experiments focused on groundwater management that are tailored to local conditions and problems. Just as there is not a national water policy, there is no overarching national vision for groundwater to guide its sustainable development. Diverse shareholders might be able to develop a shared vision based on the following ideals:

- Groundwater use must be balanced among economic development, environmental health, and quality-of-life needs for future generations.
- Groundwater and surface water should be integrated, where and when possible, for management decisions, regulations, and policies.
- Groundwater needs to be constantly "visible," not just when it is at the center of a problem or crisis.

- Trust, underpinned by transparency, is central to changing management approaches.
- Approaches that have been successful in one place should be tested elsewhere, recognizing translation and scalability challenges.
- Creating efficiencies through groundwater markets must be balanced with ensuring some level of access equality.

APPENDIX I: FORUM AGENDA

THE ASPEN-NICHOLAS WATER FORUM

DEEPENING GROUNDWATER SUSTAINABILITY

May 30 – June 2, 2017
The Aspen Meadows Resort
Aspen, Colorado

TUESDAY, MAY 30

Opening Reception and Dinner – The Meadows Restaurant

Featured Panel: Internet of Water

A special conversation discussing the newly released final report, *Internet of Water,* from the Aspen Institute Dialogue Series on Sharing and Integrating Water Data for Sustainability.

Moderated by **Martin Doyle** from the *Nicholas Institute for Environmental Policy Solutions at Duke University*, and with an introduction by **David Monsma** from the *Energy and Environment Program at the Aspen Institute.*

Panelists:

Jerad Bales, CUAHSI
Emily Read, USGS
David Totman, ESRI
Ryan Barr, E&J Gallo Winery

WEDNESDAY, MAY 31

Welcome and Introductions:

A brief introduction from the hosts around the focus and goals of the Forum.

David Monsma, Energy and Environment Program, The Aspen Institute
Martin Doyle, Nicholas Institute for Environmental Policy Solutions, Duke University

Session One: Current State of Groundwater

This session will focus on the current state of groundwater in the nation. Groundwater has historically been a black box, challenging to measure, understand, and thus to manage. As such, "sustained depletion" has been a widespread management practice, resulting in consequences such as stream depletion, declining water quality, saltwater intrusion and land subsidence. This session will set the stage by documenting trends affecting groundwater resources in the United States, drawing on case studies of aquifers being depleted and those which have been stabilized, or even partially recovered.

Discussants:

Setting the Scene	**Martin Doyle**, Duke University
Nation's Aquifers-Quality/Quantity	**Emily Read**, USGS
Ag Reliance/Concern	**Michael Frantz**, Frantz Wholesale Nursery
Industry Reliance/Concern	**Rob Bruant**, Pioneer Natural Resources
City Reliance/Concern	**Robert Laughman**, Aqua Texas

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

Session Two: How Did We Get Here?

This session will explore the history, assumptions, and practices for using and managing groundwater. What are the assumed standards of practice that have accumulated over the past two centuries—and accelerated over past decades—that have led to the current state of groundwater? What are shared policies or regulations from state to state, or city to city? What are the assumptions that large water users—whether cities or industries or farms—make that are part of our operating practices?

Discussants:

Groundwater Rights	**Robert Mace**, Texas Water Development Board
Regulating Quality & Enforcement	**Peter Grevatt**, EPA-Groundwater
Agricultural Practices	**Alan Boyce**, Materra Farming Company
Business Practices & Assumptions	**Jon Radtke**, Coca-Cola North America

Moderator: **Martin Doyle,** Duke University

Session Three: Ongoing Policy and Regulatory Experiments: What Can Translate Elsewhere?

Growing awareness of groundwater depletion and contamination have led to a recent revolution in ongoing policy and legal experiments to try to address the myriad of problems. Importantly, these different experiments are ‘hyper-localized’—they are developed and deployed at very local scales, tested, and adapted. Yet because of this, their success or failure is often not known beyond a narrow region, or at best, an individual state. This session will dive into some of the nascent policy changes that have been developed recently, as well as the impacts of policies that have been ongoing for several years, focusing on insights that might be translatable and scalable elsewhere.

Discussants:

Managing Industry Use	**Michael Teague**, Oklahoma Secretary of Environment & Energy
Practices in Eastern US	**Chuck Drake**, St. Johns Water Management District
Balancing Competing Demands	**Joe Whitworth**, The Freshwater Trust

Moderator: **Megan Mullin**, Duke University

THURSDAY, JUNE 1

Session Four: Current “Market” Opportunities in Groundwater

New groundwater policy and regulations, coupled with the realization that groundwater depletion can directly impact surface water (and water rights allocations), have created potential opportunities for using market mechanisms to manage groundwater use, reuse, and replenishment. As markets emerge, there are opportunities for environmental gains to be made by allowing the environment to have a seat at the table. Likewise, there are opportunities for new types of investments, and new sources of capital for groundwater projects. In this session, we will explore new and innovative markets attempting to address groundwater depletion. Have these markets worked and are they scalable? What are the opportunities and the challenges?

Discussants:

Markets in the High Plains	**Nicholas Brozović**, University of Nebraska
Buying Groundwater for Ecosystems	**Morgan Snyder**, Walton Family Foundation
Business Opportunities in Groundwater	**Matt Diserio**, Water Asset Management
Risks of Markets/Potential Losers	**Martin Lowenfish**, USDA

Moderator: **Martin Doyle**, Duke University

Session Five: Using Technology and Science

If we had groundwater, would we know it? Since 2002, the GRACE satellite has enabled changes in groundwater to be estimated across the nation. Furthermore, advances in data sensors have enabled real-time collection of groundwater data, coupled with advancements in modeling capabilities to understand how groundwater flows, contaminant pathways, and estimated yields, etc. At the same time, advancements in remediation technologies provide opportunities to more cost-effectively treat groundwater contamination that historically has often resulted in chronic problems and lost water resources. Technological advancements such as these provide opportunities for more precise and effective management of groundwater resources, both locally and at scale.

Discussants:

Satellites and Groundwater	**Jay Famiglietti**, NASA JPL
Monitoring for Compliance and Markets	**Marian Singer**, Wellntel
Active Treatment of Groundwater	**Wes Lobo**, Xylem
Data Sharing and Integration	**Joya Banerjee**, Bechtel Jr. Foundation

Moderator: **Robin Newmark**, NREL

Session Six: Where are the Big Opportunities?

There are a series of novel collaborations or integrations of policy and technology, or regulations and markets, or industry and NGOs that have begun to pivot conversations from 'sustained depletion' to genuine improvement. This session will provide insights into some of those novel integration experiments demonstrating how unusual combinations of sectors and people can circumvent previously recalcitrant problems.

Discussants:

Industry/NGO collaboration	**Sandy Fabritz**, Freeport McMoRan
	Laura Huffman, The Nature Conservancy
Integrated Water Management	**John Sabo**, Arizona State University
Emerging Technology and Ag	**Brian Lutz**, The Climate Corporation

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

FRIDAY, JUNE 2

Session Seven: What is the Vision for Groundwater?

A key role that a roundtable can play is to support the development of a vision for the forum topic, such as developing a national policy for water data (a product from the 2015 Forum). This final session will reflect on the discussions of the forum, and identify potential alternative futures for groundwater. What are best or worst case scenarios, and what might lead to them? What critical interventions could pivot groundwater in one direction or another? Looking forward strategically, participants will discuss how to further advance the application of new technologies and policy experiments to achieve sustainable groundwater management.

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

Forum Adjourns

APPENDIX II: FORUM PARTICIPANTS

William Alley, Director Science and Technology, National Ground Water Association

Eric Averett, General Manager, Rosedale-Rio Bravo Water Storage District

Jerad Bales, Executive Director, CUAHSI

Joya Banerjee, Senior Program Officer, S. D. Bechtel, Jr. Foundation, Stephen Bechtel Fund

Ryan Barr, Director, E. & J. Gallo Winery

Fawn Bergen, Global Program Manager, Water and Carbon Footprint, Intel Corporation

Alan Boyce, Chairman, Materra Farming Company

Nicholas Brozović, Director of Policy, Daugherty Water for Food Global Institute

Robert Bruant, Subsurface Manager, Pioneer Natural Resources

Samantha Campbell, President, The Keith Campbell Foundation for the Environment

William Cunningham, Chief, Office of Groundwater, USGS

Michael Deane, Executive Director, National Association of Water Companies

Matthew Diserio, President and Co-Founder, Water Asset Management

Martin Doyle (*Moderator*), Director, Water Policy Program, Nicholas Institute for Environmental Policy Solutions at Duke University

Chuck Drake, Governing Board Member, St. Johns River Water Management District

James Eklund, Of Counsel, Squire Patton Boggs (U.S.) LLP

Sandy Fabritz, Director, Water Resources, Freeport McMoRan

Andrew Fahlund, Program Officer, Water Foundation

Jay Famiglietti, Senior Water Scientist, Jet Propulsion Laboratory, NASA

Jack Fellows, Director, Climate Change Institute, ORNL

Catherine Flowers, Founder, Alabama Center for Rural Enterprise, Rural Development and Director, Environmental Justice and Civic Engagement for the Center for Earth Ethics

Tera Fong, Strategic Business Analyst, DC Water

Michael Frantz, President, Frantz Wholesale Nursery, LLC

Derek Gardels, Project Engineer, HDR Engineering Inc

Brian Gray, Senior Fellow, Public Policy Institute of California

Ronald Green, Institute Scientist, Soutwest Research Institute

Peter Grevatt, Director, OGWDW, EPA

Maurice Hall, Associate Vice President - Ecosystems - Water, Environmental Defense Fund

Josh Hankins, Coordinator - Rice Stewardship Partnership, USA Rice

Josh Henretig, Senior Director, Environmental Sustainability, Microsoft

Laura Huffman, State Director, The Nature Conservancy

Sherrel Johnson, Grants & Special Projects Administrator, Union County Water Conservation Board

Ted Kowalski, Sr. Program Officer - Environment, Walton Family Foundation

David LaFrance, CEO, American Water Works Association

Robert Laughman, President, Aqua Texas

Sylvia Lee, Sustainability Strategy Manager, Facebook

Wesley Lobo, Global BU Director, Industry & Agriculture, Xylem Inc.

April Long, Stormwater Manager, City of Aspen (CO)

Martin Lowenfish, Conservation Initiative Team Leader, NRCS, USDA

Brian Lutz, Senior Scientist-Biogeochemistry, The Climate Corporation

Robert Mace, Deputy Executive Administrator, Water Science and Conservation, Texas Water Development Board

Jordan Macknick, Energy and Environmental Analyst, NREL

Matthew McKenna, Principal, Open Prairie

David Monsma (*Moderator*), Executive Director, Energy and Environment Program, The Aspen Institute

Megan Mullin, Associate Professor, Environmental Politics, Duke University

Robin Newmark, Associate Laboratory Director, Energy Analysis and Decision Support, NREL

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APPENDIX IV: ACRONYMS

AF	Acre-Feet
ASR	Aquifer Storage and Recovery
ESA	Endangered Species Act
GCD	Groundwater Conservation Districts
GRACE	Grace Recovery and Climate Experiment
GSA	Groundwater Sustainability Agency
MAF	Million Acre-Feet
NGWMN	National Groundwater Monitoring Network
NORMs	Naturally Occurring Radioactive Materials
NWIS	National Water Information System
P3s	Public Private Partnerships
SDWA	Safe Drinking Water Act
SGMA	Sustainable Groundwater Management Act
UIC	Underground Injection Control
UI Labs	University and Industry Labs
USGS	United States Geological Survey