Dædalus

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Summer 2015

On Water

Inside front cover: The Mississippi River draining into the Gulf of Mexico, November 1999. The Mississippi River drains the heart of the North American continent, carrying vast quantities of nutrients that flow off of agricultural lands. These nutrients act as fertilizer for the phytoplankton in the Gulf waters. When the phytoplankton die, the process of their decomposition absorbs oxygen dissolved in the water, creating annual low-oxygen "dead zones" that are harmful to the Gulf ecosystem. Eutrophication – the delivery of excessive nutrients to surface waters – is occurring throughout the world in areas with intensive agriculture or with large human populations, causing impacts such as dead zones and harmful algal blooms. This true-color image, which appears courtesy of the NASA Earth Observatory, was acquired on November 27, 1999, by the Enhanced Thematic Mapper plus (ETM+) aboard NASA's Landsat 7 satellite. The image was visualized by Robert Simmon using Landsat data provided by the University of Maryland Global Land Cover Facility.

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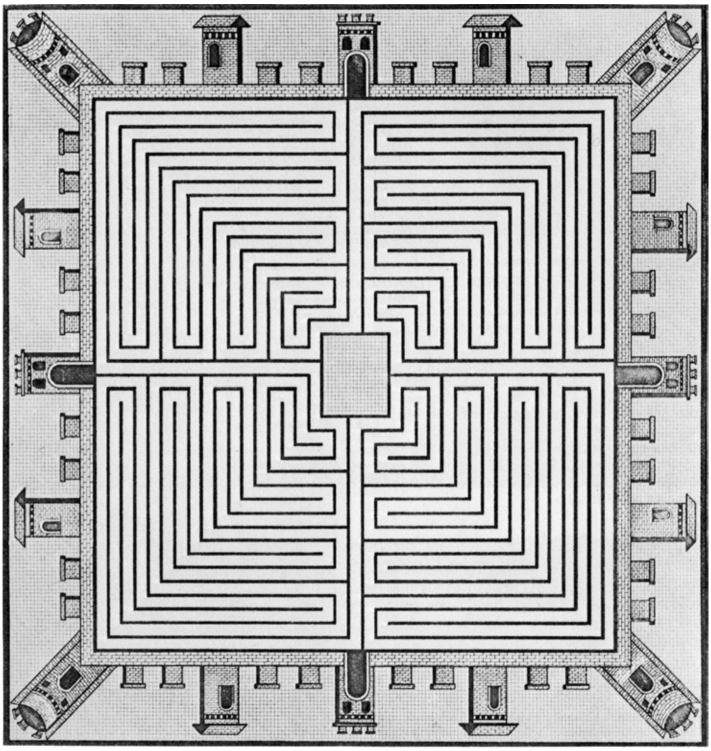

Nineteenth-century depiction of a Roman mosaic labyrinth, now lost, found in Villa di Diomede, Pompeii

Dædalus was founded in 1955 and established as a quarterly in 1958. The journal's namesake was renowned in ancient Greece as an inventor, scientist, and unriddler of riddles. Its emblem, a maze seen from above, symbolizes the aspiration of its founders to "lift each of us above his cell in the labyrinth of learning in order that he may see the entire structure as if from above, where each separate part loses its comfortable separateness."

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Introduction

Anna M. Michalak & Christopher B. Field

There is no resource more central to life on Earth than water, and its role in shaping the arc of human history cannot be overstated. Whether through its presence or absence, water has both fueled the growth of the world's great societies and hastened their demise. Humanity's need for water is inextricably linked to its need for security, energy, food, and community. At the same time, climate change, population growth, and economic development are currently placing unprecedented demands on this limited resource, as well as increasing the uncertainty associated with future demands and availability. As with all limited resources, both challenges and opportunities emerge as resources become scarcer; it is how societies and ecosystems respond to such "stresses" that determines their fate.

When we first embarked on the development of an issue of *Dædalus* on the topic of water, we considered a number of ideas about how to organize and frame both the individual contributions and the issue overall. As researchers focusing on the functioning of the earth system and humankind's role in altering this system, the challenges surrounding humanity's use of – and need for – water seemed to us all too clear. Rather than organizing the collection of articles around a series of problems and failures, however, we were quickly drawn instead to the idea of framing current issues within the context of the decisions that we face and the opportunities that emerge as we are confronted with increasing demands on a limited resource. We hope that we have

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been successful in this endeavor, and that a sense of opportunity accompanies the sense of severity and urgency in the individual perspectives that make up this collection. If necessity is indeed the mother of invention, then we must be on the cusp of some unprecedented creativity!

It has been an honor and a great pleasure to work with some of the world's leading water scholars as this special issue has taken shape, and it is with great excitement that we share the final product with the readership of *Dædalus*.

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Water, Climate, Energy, Food: Inseparable & Indispensable

Christopher B. Field & Anna M. Michalak

Abstract: Water issues are rarely simple. At the global scale, water is at the focus of a powerful multifaceted challenge. Demands for both consumptive and nonconsumptive uses are growing, while climate change is at the same time decreasing availability in some places and increasing risks of heavy precipitation in many others. Through diverse mechanisms that interact with natural processes, human activities impact not only the quantity of water available but also its quality. Here we explore the multiway interactions among water, climate, energy, and food through a number of case studies illustrating the interconnected web of competing drivers, demands, and trade-offs that frame humanity's decisions about water use. The net result of this complex mix of drivers and processes is that water issues need to be addressed with a systems perspective. While a systems framing can be daunting, integrated approaches are fundamental to identifying and evaluating options for sustainable solutions.

Water is integral to life on Earth. It is essential to the survival of people, organisms, and economies. But issues surrounding water resources and management are not rooted in the question of whether there is enough water on our planet; rather, they are driven by the state of the water available to us. Is the water salty or fresh? Is it frozen or liquid? Is it clean or contaminated? Is it here or elsewhere? Is it available when it is needed, or does it arrive when it is harmful? The effectiveness of strategies for dealing with water availability, quality, and variability is a defining determinant of the persistence of species, the functions of ecosystems, the vibrancy of societies, and the strength of economies.

How can we describe the world's water? Water on Earth can be divided into five main pools totaling 1.38 billion cubic kilometers. Water vapor in the atmosphere is the smallest pool, making up less than 0.001 percent of the total.[1] Lakes, rivers, and streams hold about 0.013 percent of Earth's water, of which nearly half is in the form of salty lakes. Groundwater holds about 1.7 percent of the total, but, again, more

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than half of all groundwater is salty. Ice caps and permanent snow – including the massive continental ice sheets on Antarctica and Greenland, alpine glaciers, and seasonal snow – constitute another 1.7 percent of the total. The fifth and largest pool comprises the oceans of salty water, making up 96.5 percent of Earth's total. Put another way, only about 2.5 percent of the world's water is fresh; the remainder is salty. About half a million cubic kilometers of water, or 0.036 percent of the total, evaporates and falls as precipitation each year. Of this, about 21 percent falls on land – more than one half of which evaporates directly back into the atmosphere – while the remainder falls back to the oceans.

Relative to the enormity of the total, human impact on Earth's water may initially appear quite small. For example, the total water in ice on land has been decreasing by about three hundred cubic kilometers per year as a result of warming temperatures and changing precipitation patterns,[2] and groundwater that serves the world's arid and semiarid areas has been decreasing by about one hundred fifty cubic kilometers per year as a result of human extraction.[3] The total water footprint of human activities (all of the water used for crops, manufacturing, and domestic purposes) is on the order of seven thousand five hundred cubic kilometers per year.[4]

But, as we will see, the effects of our water use are massive. Much of the challenge of understanding and managing water arises from the fact that it is central to so many activities. As a consequence, decisions about water often tell us more about our priorities than they do about the total amount of available water. Many of the trade-offs in allocating water involve three big water users: food, energy, and environment. A world with an increasing human population, burgeoning energy demands, evolving food preferences, and a rapidly changing global climate means that everything about the water equation is dynamic. The result is a complicated web of interconnections with potentially unexpected risks, but also with many points for intelligent intervention.

Changing the distribution of water among pools, storing huge quantities of water, or moving water long distances is feasible at a scale that is modest relative to global totals but that is crucial locally. The constraints are physical (as with the large inputs of energy required for desalination), geographical (many of the logical locations for reservoirs have already been used), financial (building and sustaining the infrastructure required for managing water is expensive), political (nobody wants to relinquish rights to scarce water without compensation), and ethical (what uses deserve to be prioritized, and how do they relate to the needs of the environment?).

In this essay, we survey the multidirectional linkages and interactions among water, climate, energy, and food production, outlining major features of these relationships and developing case studies on a few of the connections that illustrate the diversity, richness, and difficulty of the management challenges. This essay also serves as a springboard for the essays that follow, which dive more deeply into particular challenges, contexts, and solutions. Michael Witzel explores – through the lens of water in mythology – the cultural and spiritual depths of the link between humankind and water. John Briscoe writes about the need for and the success of engineered water systems, as well as the associated compromises required for meeting diverse demands. Adena Rissman and Stephen Carpenter consider nonpoint source pollution (the runoff of pollutants from agricultural or urban land into lakes and rivers) and our options for addressing it. Jerald Schnoor focuses on the issue of sustainability, surveying practices that lead to unsustainable water management systems and pointing toward some remedies. Katharine Jacobs and Lester Snow explore ways in which adaptation can help human users cope with limited resources. Richard Luthy and David Sedlak consider technology-based solutions to increasing water demands, including desalination, long-distance transport, and reuse/recycling. Terry Anderson analyzes the current state and potential role of water markets in improving water allocations. Finally, Charles Vörösmarty, Michel Meybeck, and Christopher Pastore take a historical perspective, painting a picture of how our aspirations for, and investments in, water management have changed over time.

The concepts of trade-offs and cycles are fundamental to understanding the linkages among water, climate, food, and the broader environment. For many kinds of water uses, allocation to one use intrinsically means less water for other uses. Consumptive use for agriculture, industry, or cities almost always involves trade-offs, as do mandates for instream flows to protect ecosystems or fisheries. But even consumptive use leaves the total amount of global water unchanged; the real issue is that consumption shifts water to a different part of the hydrological cycle: for example, from liquid to vapor, clean to contaminated, or fresh to salty. Choices about managing water trade-offs involve more than hydrology and economics. They involve values, ethics, and priorities evolved and embedded in societies over thousands of years. The juxtaposition of hydrology, economics, and values is at the crux of the water-climate-food-energy-nature nexus.

Water and climate are inextricably linked. Climate defines the amount, variability, and type of precipitation; the rate of evaporation; and the conversion of water to its various phases (snow, ice, liquid, vapor). Climate also influences how water moves through land and water bodies, and how it changes throughout the journey. Climate *change* alters all of these processes.

For some processes, the impacts of recent and future climate changes are clear. For others, the complexity of the climate system and the uncertainty of future human actions make both detection of past changes and prediction of future patterns fiendishly difficult. At the simple end of the scale, a warming climate leads to a global increase in evaporation, which in turn leads to an increase in global precipitation. On the other end of the scale, it is far more difficult to understand how changes in temperatures, cloud cover, the incidence and intensity of extreme meteorological events, and other aspects of a changing climate will impact our ability to provide a stable, plentiful, and safe supply of water within the context of a growing global population. We will use two examples to illustrate the complex and multifaceted interactions between climate and water availability: water quantity and the role of extremes; and water quality and the links to eutrophication.

The spatial patterns and intensity of precipitation are far from uniform, and climate change only increases this variability. The general pattern is that wet regions tend to experience increased precipitation, while dry areas tend to get drier, thereby leading to increased risks of both wet (flooding) and dry (drought) extremes.[5]

Many parts of the world have already experienced an increase in the fraction of all precipitation that falls in the heaviest weather events (which are more likely to lead to flooding).[6] A warmer atmosphere can hold more moisture, increasing the likelihood of conditions that release huge amounts of precipitation over a short period of time. As a consequence, flood risks can rise even while increased evaporation is challenging water supplies. In the Eastern and Midwestern United States, which have experienced an increase of more than 30 percent in heavy downpours over the last fifty years, the motivation for recognizing and preparing for an increased risk of heavy rainfall is clear.[7] One recent paper concluded that 18 percent of moderate precipitation extremes over land (in addition to 75 percent of moderate heat extremes) are a result of global warming that has already occurred.[8]

Conversely, the trend toward drying is amplified by increased evaporation caused by warming, reflecting not only more rapid moisture loss from reservoirs but also increased water demands for crops and natural ecosystems. With warming, many areas will face increased risks of severe water shortages, even if average precipitation does not change.

Beyond precipitation, climate change is also altering global patterns of the physical state of water. In most regions, climate change is leading to decreases in snow and ice. In areas with winter temperatures not too far below freezing, even modest warming can lead to a dramatic decrease in the fraction of precipitation that falls as snow. For example, although California's record-breaking low snowpack in spring 2015 is partly a reflection of low precipitation, it is also a consequence of warmer storms that bring rain instead of snow, reducing the ability of mountainous regions to store water for dryer seasons. The melting of alpine glaciers further threatens water supplies, especially in parts of Asia and South America, where thaw leads initially to an increase in river flow and eventually to a loss of year-to-year buffering.

Worldwide, rates of melting are exceeding rates of new ice formation. Over the last two decades, melting has outpaced ice accumulation, leading to net losses of ice mass in Greenland, Antarctica, and alpine glaciers. From 2005 to 2009, the rate of loss was about three hundred cubic kilometers per year, contributing to a bit less than one millimeter per year of global sea-level rise.[9] Melting of continental ice has the potential to cause large amounts of sea level rise: for example, the quantity of ice on Greenland is sufficient to raise global sea levels by over seven meters; the ice on Antarctica represents about *seventy* meters of potential sea-level gain. And while much of Antarctica is too cold to be at serious risk of melting, the West Antarctic Peninsula, representing close to five meters of potential sea-level rise, is not. Melting continental and sea ice also amplify warming by replacing a white, reflective surface with a dark surface that absorbs much of the incoming sunlight. The same principle explains why you stay cooler on a hot day by wearing a white, rather than black, shirt. The numbers are daunting: in 2012, the annual minimum in Arctic sea ice was about three million square kilometers fewer than the 1981–2010 average.[10]

Although water availability is classically thought of in terms of *quantity*, water is useful (usable) only if it is of sufficient *quality* for its intended purpose. And water quality is critical regardless of its intended use, whether it be used by humans directly for consumption, recreation, sustaining fisheries, and irrigation, or by the broader ecosystem to support aquatic life, for example. This broader context of water availability and water quality is directly linked to changes in climate via impacts on meteorological conditions, as alluded to above.

The link between climate and water quality is perhaps most poignantly illustrated through the lens of coastal and freshwater eutrophication: the delivery of excessive nutrients – nitrogen and phosphorus are typically the most concerning – to water bodies from agricultural production as well as from urbanization and other human activity. The effects of eutrophication are many, but some of the most common and worrisome are harmful algal blooms by toxin-producing species of phytoplankton and widespread low-oxygen "dead zones" – in which the decomposition of organic matter consumes nearly all of the dissolved oxygen – that disrupt aquatic food chains and can lead to massive fish kills. Hundreds of coastal and inland water bodies globally are already routinely impacted by harmful algal blooms and hypoxia, including many in North America. A harmful algal bloom in Lake Erie in 2011 stretched across five thousand square kilometers, an area larger than the state of Rhode Island.[11] The dead zone in the lake the very next year was estimated at close to nine thousand square kilometers, an area larger than the state of Delaware.[12] In August 2014, a pileup of toxin-producing cyanobacteria from that year's algal bloom near the Toledo, Ohio, water intake shut down the city's water supply for two days.

What is the link to climate? Although the excess nutrients nominally result from land management practices, their delivery to water bodies and the effects they engender once there are highly dependent on weather patterns, which are themselves evolving in response to climate change. Variations in precipitation, whether the amount of rain, its seasonality, or the intensity of storms, affect how much nitrogen and phosphorus are flushed into waterways. Temperatures control conditions in the water, including when the water is warm enough to sustain blooms and the degree of stratification, which prevents cold (heavy) water from being replenished with oxygen due to warm (light) water acting as a lid. Wind affects stratification – with stronger winds helping to mix the water column – as well as water flow (and therefore nutrient transport) within water bodies. All of these interconnected processes are changing with the climate. In the case of Lake Erie, extreme springtime precipitation in 2011 followed by warm and quiescent conditions helped supercharge the bloom. In 2012, an intense drought led to stagnant conditions that supercharged the dead zone. And, as we saw in the previous section, extreme meteorological events are becoming more common and more intense, loading the dice for more extreme eutrophication, with impacts to aquatic ecosystems and beyond.

The global energy system relies massively on water, either as a direct energy source (hydropower) or for cooling (electricity generation), irrigation (biofuels), or extraction (hydraulic fracturing). Over one-third of freshwater withdrawals in the United States are used for cooling thermoelectric energy generators. Preparing and using the water to support energy production – a process that includes collection, cleaning, transportation, storage, and disposal – itself involves massive amounts of energy. This interdependence has sometimes been referred to as the *water-energy nexus*. The interface between water and energy invariably also introduces a number of debates about alternative uses of water and impacts on water availability (quantity and quality). We use two case studies to exemplify some of these challenges here: alternative energy sources, and traditional energy production.[13]

As global energy demand continues to grow, and as the climate impacts of fossil fuel–based energy sources become untenable, increasing emphasis is being placed on renewable sources of energy. These sources of energy are rightfully considered more sustainable than energy that relies on nonrenewable energy sources. The sustainability of specific technologies, however, must be assessed within the context of their reliance and impact on water resources.

The need to assess the implications of alternative energy production for water is perhaps nowhere more poignant than in the case of biofuels. We are accustomed to thinking about the energy requirements of our vehicles in terms of miles per gallon, a measure of fuel efficiency. The unit against which we measure efficiency is, of course, a gallon of gasoline. But what if it were a gallon of water? The water requirements of corn-based or soybean-based biofuels translate to a fuel-efficiency value of less than 0.1 miles per gallon of water! The vast majority of this water is used for growing crops, rather than for converting them to biofuels. Currently, about 40 percent of the U.S. corn crop is used for ethanol production.[14] When ethanol is produced from corn grain, the water footprint is about two hundred gallons of water per gallon of ethanol, greater than the average per person water use of one hundred twenty gallons per day.[15] In the case of rain-fed production, the cost in water is of relatively little consequence; but in the case of irrigated production, the heavy water demands inevitably come at the expense of other uses.

High water demands, combined with the uncertainty surrounding future water availability due to changes in climate, point to the need to carefully consider the water implications of alternative energy choices. For example, the water requirements of wind and solar energy production are dramatically lower than those of biofuels, and lower also than even some "traditional" energy sources.

In the case of biofuels, the role of water is clear and intuitive: crops need water to grow. In the case of hydropower, the role of water is also self-evident. The water "cost" of other energy sources, however, is less apparent.

Consider electricity production. The generation of electricity, which involves both "consumptive" and "nonconsumptive" uses, accounts for approximately 40 percent of freshwater withdrawals in the United States, most of which is used for cooling.[16] Although it is tempting to think of nonconsumptive uses – in which water is withdrawn from surface water or groundwater but is returned after use – as having no net impact on water resources, this is not the case. First, in the case of droughts or other decreases in available water supply, power generation can be disrupted due to a lack of sufficient cooling water. More commonly, however, challenges arise from the fact that water, once used for cooling, is not returned to the environment in its original state. For example, while much of the water used for cooling is returned to a river or lake, aquatic ecosystems are not very tolerant of heated water. In most of the United States, this constrained tolerance is addressed through regulations that limit the temperature in lakes and rivers that receive waste heat from power plants. Low water levels and warming can conspire to limit electricity generation – including not only fossil but also nuclear thermoelectric power plants – during periods when electricity demand is at its peak.

Globally, agriculture accounts for approximately 86 percent of consumptive water use.[17] Rising populations and rising living standards combine to create rapid increases in global demand for food, especially food with a high land and water footprint, such as meat. Ensuring a secure food supply is therefore inextricably linked to the availability of plentiful clean water for growing crops. Predictable water availability is critical both for rain-fed and irrigated agriculture, and uncertainty about water availability compounds uncertainty about future food security. Water quantity and quality are also integral to nonagricultural sources of food, such as fisheries. Whereas lack of water (drought) is typically understood to be a limiting factor for food production, too much water and water at the wrong times in the growing season are also major challenges facing global food production. Furthermore, food production not only requires water, but also impacts waters not directly used in production: mechanisms include runoff of sediment and nutrients from agricultural areas into receiving waters, as well as the water-quality consequences of large-scale aquaculture (the farming of aquatic animals and plants). We again use two case studies to exemplify the interconnections between water and food: the water demands of food production, and its downstream impacts.

Plants grow by using the energy from sunlight to convert carbon dioxide in the atmosphere into carbohydrate and, eventually, more plant. But plants on land cannot take up carbon dioxide without losing water. The pathway by which carbon dioxide enters and leaves is the same as the path by which water evaporates. The ratio of water loss to carbon dioxide uptake varies with carbon dioxide concentration and atmospheric humidity, as well as among plant species. In most habitats, plants lose fifty to one hundred and fifty gallons of water through evaporation – a process called *transpiration* when the water comes from leaves – to make a single pound of new plant. This mechanism underlies a massive water footprint for food, whose size depends not only on the amount of water transpired per unit of plant growth but also on the fraction of the plant consumed as food or on the amount of plant required to produce each unit of consumable animal product.

The water footprint of various foods (Table 1) limits the size and sustainability of the agriculture enterprise in any location. In regions of rain-fed agriculture, the link between water inputs and crop outputs has a clear upper boundary determined by the amount of plant growth per unit of water transpired. Many processes can reduce yields below this boundary: runoff and deep drainage; processes that move the water out of the zone accessible to plant roots; and constraints from too much water, poor soils, unfavorable temperatures, pests, or other management challenges. Much of the history of rain-fed agriculture can be understood as an effort to consistently get yields to the upper boundary set by water availability.

Irrigation can substantially increase yields and year-to-year predictability. About 33 percent of the world's crops come from the approximately 25 percent of cropland that is irrigated worldwide.[18] In areas that are sometimes wet enough for rain-fed agriculture, irrigation can enhance water availability through dry periods. Irrigation can also allow the extension of agriculture into areas that are otherwise too dry. But irrigation is viable only if there is excess water to tap. Locally, this can mean groundwater that is recharged during wet periods; regionally, it can mean snowpack, rivers, streams, lakes, and reservoirs.

The water footprint of food production is ripe for improvement. Improving irrigation practices or technology can be robust and cost effective. Crop yields (higher yields lead to lower water footprints) and climate also play a large role in regional differences in water footprint. Decreasing the water footprint of food production through crop choice or breeding also present opportunities for gains. For example, some crops – notably corn and sugarcane – have a carbon dioxide concentrating mechanism called C_4 photosynthesis that enables them to use less water than most other crops. Breeding C_4 photosynthesis into crops like rice and wheat, thereby increasing their water efficiency, is one of several strategies subject to active research. The water footprints for meat (especially beef), eggs, and dairy are several-fold larger than for crops, essentially because animals are

Table 1
Average Water Consumption for Producing Food Products

Food product	Water consumption (gal/lb)
Rice	356
Wheat	160
Corn	109
Soybeans	214
Sugar cane	21
Eggs	400
Milk	119
Cheese	589
Beef	1857
Pork	582
Sheep	736
Chicken	469

Average consumption incorporates often substantial regional differences due to climate and management. Source: Arjen Y. Hoekstra and Ashok K. Chapagain, "Water Footprints of Nations: Water Use by People as a Function of Their Consumption Pattern," *Water Resources Management* 21 (2007): 35–48.

not very efficient at converting plant calories into animal biomass. Globally, rising preferences for meat-rich diets represent one of the largest drivers of increased water demand.

Agriculture not only uses water, but also has downstream impacts via the water that runs off the fields or seeps into the ground. The unprecedented growth in agricultural production of the last century has been enabled in large part by the use of fertilizers. In the last decade, the drive toward the production of biofuels is putting further pressure on the agricultural system. Total U.S. corn production has increased from seven billion bushels in 1995 to fourteen billion bushels in 2014, almost entirely due to the explosion in production of corn for fuel.[19] Over ninety million acres were planted with corn in the United States in 2014, an area the size of Montana or double the size of all New England states combined. Further, corn requires more fertilizer per acre than any other major U.S. crop.

When water leaves agricultural fields, whether through runoff, seepage, or drainage, it carries with it nutrients that have not been assimilated into the soil and crops. While the total acreage devoted to agriculture has changed little since the 1950s, the total amount of commercial fertilizer used on that land has more than doubled. This has led to increases in agricultural productivity, but also in the amount of nutrients washing off fields and into waterways. That nutrient runoff results not only in the contamination of coastal and inland water bodies, but can also lead to massive algal blooms and dead zones.

Agricultural management strategies are evolving as well, and some are further contributing to the increased flushing of nutrients into waterways. One interesting example is the use of conservation tillage or "no-till" as a replacement for conventional tillage. This shift in practice was encouraged in part for environmental reasons: namely, to reduce erosion from agricultural fields. From the perspective of downstream impacts, however, the results are mixed. While erosion is decreased, conservation tillage and no-till leave fertilizer on the surface of the soil, thereby making it more vulnerable to runoff in the event of precipitation. In the case of tile drainage, which removes excess water from the soil (preventing it from harming crops), the additional drainage also facilitates flushing of nutrients from fields to waterways.

The environmental interests of inland and coastal water bodies appear to be increasingly at odds with the interests of the agricultural system. That said, an antagonistic view of the situation is overly simplistic. Ultimately, neither farmers nor fish are interested in fertilizer ending up in lakes rather than in fields. Identifying remedies that recognize the central role of water in agriculture (both in terms of water supply for feeding crops and in terms of downstream vulnerabilities), as well as the complexity of nutrient delivery and impacts to waterways, will require a *systems approach*. Such an approach will need to recognize that each change made to one part of the system affects all other components, and future changes in management need to address not only the intended goals but also other, often unintended concurrent consequences. This will be especially important as demand for crops continues to grow and concerns about food security grow along with it.

At the global scale, water is at the focus of a powerful multifaceted challenge, with each water demand amplifying the difficulty of responding to the others. Together, this water-energy-food-nature nexus can create a perfect storm. All of these pressures coexist in an environment in which the human population is growing rapidly not only in size, but also in wealth, demand for energy, and demand for diets rich in meat. In percentage terms, the rate of human population growth has fallen dramatically over the last several decades, but the human population is still growing by over 1.1 percent per year, meaning one million new water consumers every five days. Climate change is complicating the task of ensuring water availability: it decreases available supplies, degrades storage in snowpack and glaciers, and increases the fraction of precipitation that comes in the heaviest storms. Further, energy production puts huge demands on water availability. While many of the demands of the energy system, especially for cooling and hydroelectric power, return the water to the river, these uses still produce major environmental consequences. Consumptive uses for fossil fuel extraction generate large amounts of contaminated water that requires disposal. And the production of crops for biomass energy is a huge consumer of water.

Where does all of this leave the needs of nature? Over the last few decades, many of the high-profile conflicts over water have involved allocation disputes between consumptive uses and instream flows needed to sustain rare or endangered species. Instream flows, uncontaminated lakes, and watersheds also provide a wide range of valuable goods and services; thus, allocating water for nature is about more than just protecting fish. It is about protecting the viability of Earth's life support system.

ENDNOTES

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Water in Mythology

Michael Witzel

Abstract: Water in its various forms – as salty ocean water, as sweet river water, or as rain – has played a major role in human myths, from the hypothetical, reconstructed stories of our ancestral "African Eve" to those recorded some five thousand years ago by the early civilizations to the myriad myths told by major and smaller religions today. With the advent of agriculture, the importance of access to water was incorporated into the preexisting myths of hunter-gatherers. This is evident in myths of the ancient riverine civilizations of Egypt, Mesopotamia, India, and China, as well as those of desert civilizations of the Pueblo or Arab populations.

Our body, like the surface of the earth, is more than 60 percent water. Ancient myths have always recognized the importance of water to our origins and livelihood, frequently claiming that the world began from a watery expanse.

Water in its various forms – as salty ocean water, as sweet river water, or as rain – has played a major role in human tales since our earliest myths were recorded in Egypt and Mesopotamia some five thousand years ago. Thus, in this essay we will look toward both ancient and recent myths that deal with these forms of water, and we will also consider what influence the ready availability (or not) of water had on the formation of our great and minor early civilizations.

Many of our oldest collections of myths introduce the world as nothing but a vast salty ocean. The oldest Indian text, the poetic *Ṛgveda* (circa 1200 BCE), asserts: "In the beginning, darkness was hidden by darkness; all this [world] was an unrecognizable salty ocean [*salila*]."[1] This phrase is frequently repeated by later Vedic texts with the mythic formula: "In the beginning there was just the salty ocean."

Mesopotamian mythology, in its Babylonian form, differs somewhat: there was both salty water and sweet water, which mingled to produce the gods.

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"When on high heaven had not been named . . . Nought but primordial *Apsu* [the watery abyss], their begetter, and *Mummu-Tiamat*, she who bore them all, their waters, commingling as a single body . . . then it was that the gods were formed within them."[2]

Ancient Maya mythology, as recorded in the sixteenth-century *Popol Vuh*, reflects the same concept: "Only the sky alone is there . . . Only the sea alone is pooled under all the sky. . . . Whatever there is that might be is simply not there: only the pooled water only the calm sea, only it alone is pooled."[3]

Or, according to the first chapter of the Hebrew Bible: "In the beginning the gods[4] created heaven and earth . . . and the spirit [*ruah*] of the gods[5] hovered over water." The Christian King James Bible revised this to read: "In the beginning God created the heaven and the earth. . . . And the spirit of God moved upon the face of the waters."

In ancient Egypt, in the book of overthrowing the dragon of the deep, *Apophis*,[6] the "Lord of All," explains, "I am he who came into being as *Khepri* . . . I was . . . in the Watery Abyss. I found no place to stand." Here and in the Biblical case, one or more deities predate the actual act of creation, a characteristic shared with other creation mythologies, such as with the Winnebago of Wisconsin: "Our father . . . began to think what he should do and finally began to cry and tears began to flow and fall down below him . . . his tears . . . formed the present waters."[7]

Other Native American peoples agree, though not on all details. The Maidu of California, employing a motif that also appears in Siberian mythology, state: "In the beginning . . . all was dark, and everywhere there was only water. A raft came floating . . . in it were two persons."[8] In all these examples, which primarily originate from north of the equator, the initial stage of a primordial ocean (or void) is followed by stages that lead to the emergence of the inhabitable world and finally the first humans.

The myths of sub-Saharan Africa (and Australia) are structured differently from those mentioned in that they stress foremost the origins of humans, not of the world.[9] Even then, rather exceptionally, the Boshongo in the Luanda area of Angola let the world begin with water *and* a preexisting deity: "In the beginning, in the dark, there was nothing but water. And Bumba was alone . . . he vomited the sun."[10]

Clearly, distinct from such concepts as primordial chaos (Greece) or darkness (Polynesia), the concept of water pervades many ancient and recent creation mythologies. Questioning the universality of *why* leads to psychology and, perhaps, to Jungian archetypes, though we cannot here explore the psychic origins of myths, whether due to universal characteristics of the mind or other human factors. Ethnologist Leo Frobenius and anthropologist Hermann Baumann pointed toward other explanations: namely, the spread of many myths by diffusion from an ancient center. More likely still is the development of our original myths (of the "African Eve") in East Africa, which then spread along the shores of the Indian Ocean to Australia and South China some sixty-five thousand years ago, before finally expanding into the rest of Eurasia and the Americas.[11] Consequently, all humans have a few myths in common (though that is denied for "theoretical reasons" by scholars such as the folklorist Alan Dundes). For example, the flood myth is universal: it is found all over Africa, Australia, Eurasia, and the Americas. Further, both the southern and northern versions of the myths share the common theme of shamanism, which is part and parcel of many smaller local and major religions to this day.

As the Mesopotamian example indicates, there is an important distinction between sweet water and salty water.[12] Sweet water is obviously more important for the sustenance of humans; thus, from the *Ṛgveda* onward, the ancient Indian texts praise the flowing sweet waters but not stagnant ponds ("tanks").[13] Indian texts regard rivers as goddesses, and the term "inviolate ladies" refers to their beneficial waters (which are believed to carry milk for women and semen for men). In Indian mythology, the *cakravāka* bird actually distinguishes between their water and milk.

Rivers are also invoked as sources of healing. Closely related is the ancient Indian and Iranian (Zoroastrian) idea of the river goddess *Sarasvatī*, "she who has many ponds." Sarasvatī is the modern Helmand River in Southern Afghanistan, which has given its name (*Haraxvaitī*) to the ancient province of Arachosia. It swells in spring after the snow melt, while the Sarsuti, its Indian counterpart northwest of Delhi, swells in the monsoon season. *Haraxvaitī*'s rushing waters – or further downstream, its murmuring flows – gave rise to the belief that *Sarasvatī* is the goddess of speech and poetry. Indeed, almost all Indian rivers are regarded as female, with the major exception of the male Indus (*Sindhu*; Greek *Indos*), who has given his name to the subcontinent.[14]

Female river names, usually ending in *a*, are found throughout the regions of the Indo-European language family, from Iceland to Bengal: the Seine (*Sequana*), Thames (*Tamesis*), the Central European Elbe (*Albis*), Weser (*Visara*), Saale (*Sala*), Wistla/Weichsel (*Vistula*), and the Vltava/Moldau (Czech Republic), Drava (Slovenia; or *Drau* in Austria), Drina (Bosnia), Volga (Russia), and *Gaṅgā*/Ganges (India) are all feminine.

There are, however, quite a few male Indo-European river exceptions, such as the Rhône (*Rhodanus*), Rhein (*Rhenus*), Danube (*Danubius*; now feminine as *Donau* or *Dunarea*), Tiber/Tevere (*Tiberis*), Po (*Padus*), as well as the Ebro, Tejo/Tajo, and Brahmaputra (India). Closer to home, we have the Ol' Man River, the Mississippi, the Rio Grande, and the Colorado.

The mythical cleansing power of rivers is perhaps best demonstrated by the bathing festival *Kumbh Melā*, in which millions of Hindu pilgrims assemble every twelve years at the confluence of the Ganges and Jumna rivers with the mythical, underground *Sarasvatī* at Allahabad (*Prayāga*).[15] The purifying bath delivers people from their *karma* and allows them to go to heaven after death. This belief has a long prehistory: taking a bath at certain confluences is followed by a march upstream toward the "world tree" situated in the lower Himalayas.[16] The pilgrims believe that at the meeting point of the river and the sky, one can climb up to heaven. As a result of these beliefs, a bath at any confluence of two rivers (*triveṇī*) is regarded as sacred and salvific.

Reality obviously differs considerably. By now the Jumna is virtually a sewer due to the untreated waters of Delhi and other big towns upstream. The Ganges has not fared much better. Its river dolphins are fast disappearing, and the organized "clean-up campaigns" have not had much success. Nevertheless, local folklore about the Ganges' cleanliness persists: the river "cleans itself" in spite of all its garbage, sewage, and half-cremated dead bodies. In fact, people not only bathe in the river, they also collect it to carry home over long distances; some habitually drink it. Such is the power of myth.

Water is used as a spiritual cleansing agent in diverse traditions inside and outside India, effectively blurring the boundary between cleaning and cleansing.[17] In Japan, upon entering a Shintō shrine, visitors must cleanse themselves with water;

and Islam dictates that adherents wash their hands, faces, feet, and parts of their head before prayer in an act called *Wuḍū*.[18] Washing hands for purification was also common among the Greeks and Romans, and Pontius Pilate famously did the same in an attempt to remove himself from Christ's death.[19]

In ancient Israel, too, water was used for various types of purification, including the consecration of Levites and before priests approached the altar.[20] Individuals purified themselves from guilt by washing hands and giving offerings. The cleansing and salvific force of water is also obvious in the Christian rite of baptism, irrespective of how much water is used (complete submergence in a natural body of water versus a gentle blessing of holy water). Baptism places the baptized on a path toward heaven, just like the Indian bath at the *Kumbh Melā*.

Rain is welcomed in traditions worldwide, especially those rooted outside of colder and temperate climates. Innumerable prayers and rituals are performed to attract rain – an essential source of water for drinking and agriculture – to areas that do not receive regular precipitation, such as the Mediterranean winter rains, but instead depend on unpredictable precipitation, like the summer monsoons in India, Southern China, or Japan.

Similarly, the Hopi, living in the desert of Northern Arizona, depend on the spotty summer monsoon and on winter snow for the success of their crops of corn and beans. They therefore invite many of the roughly two hundred Katsina spirits from the nearby snowy mountains to bring rain. Secret rituals are performed in underground sacred chambers (*kiva*), while dances – with humans impersonating the Katsina – are performed outside.

In India and Nepal, priests perform various rituals and help stage great monsoon festivals to ensure the timely beginning and end of the rainy season, on which the rice crops depend. The Jagannātha Festival at Puri in Eastern India is one famous example, featuring a giant "juggernaut" chariot carrying Hindu deities through town. In the Kathmandu Valley, there are two large, historically multilayered chariot festivals: the Indra Jātrā and the Macchendranāth Jātrā, both of which are celebrated to stop excessive rain. Furthermore, the divine *Nāgas* – moisture loving, snakelike, and shape-shifting beings – have their own festival at the onset of the rainy season, announced by the ritual of humans pasting an image of the *Nāgas* above their front door. There are folklore practices as well, such as burying a clay image of a rain-loving frog in a newly dug up rice field (to deliver rains).[21] The connection between monsoon rain and revitalized frogs can be traced back to the oldest Indian text, the *Ṛgveda*.[22] And should the rains fail, a village may send naked women out into its streets to dance and entice *Indra*, the god of rain.

Similar customs were observed just one hundred years ago along the river Rhine, in Serbia and Greece: a small naked girl was led into a river and hit with twigs. Or in Tyrol, Austria, young women caught on the road could have water poured over them to induce rain. The same idea may underlie the famous water festivals of Burma, Thailand, and Yunnan, which are carried out at the height of the hot season before the monsoon. Buckets of water are poured on passers-by, especially by young men chasing young women; or showers from a standpipe are splashed on onlookers.

An ancient Iranian text contained in the *Avesta* provides a dramatic account of how the star Sirius (*Tištriia*) fights with his opponent *Apaoša*[23] at the mythical lake *Vourukaša* until fog and clouds rise and rain covers all "seven parts of the earth."[24]

The many "methods" used to attract rain are all based on the shared belief that similar actions result in similar outcomes (sympathetic magic). In some parts of India, such as in Maharashtra, one ceremoniously "marries" two frogs to stop a drought and induce rain.[25] At least since the early eleventh century in parts of Europe and Algeria, humans or animals are ceremoniously dunked in rivers and ponds to attract rain. In many traditions, rain is regarded as the tears of deities: the Maori of New Zealand believe Heaven cried after he was pushed up and forever separated from his wife, the Earth.[26] In early India, however, rain was divine urine.

In many areas of the Greater Near East, the weather god – similar to the thunderer Zeus and the Indian rain god *Indra* with his troupe, the Marut – was regarded as the dominant deity. Memories of this pagan incarnation persevere: the Icelandic Thor is commemorated every Thursday (Thor's day) or the German *Donners-tag* (day of Thunder).

Because deities tend to live on mountains, pilgrims may travel to the mountains from great distances to ask for rain. If making the request directly to a deity is not an option, there are alternatives: the newly introduced Tantric Buddhism in eighth-century Japan allowed for religious rituals to be performed for the emperor in a period of drought. Across the East China Sea, the Chinese thunder god *Lei-shih* was a significant deity, more so than, for example, the river God *Ho po* of the Huang He (the Yellow River).[27]

The rainbow – prominently connected with rain – also plays a great role in various mythologies. In ancient India, and still with the pagan Kalasha people who live on the border east of Afghanistan, the rainbow is regarded as the bow (*Indradyumna*; *Indron*) of the great warrior and rain god Indra.

According to common European folklore, either treasure or a dragon – the monstrous reptile guarding hidden treasure – awaits visitors at the end of a rainbow. The rainbow can also function as a bridge between heaven and earth, such as in Southern Germany, in the Icelandic *Edda*, or in Japan. The Roma (Gypsies), originally from Northwestern India, believe that at Pentecost, it is possible to mount the rainbow and ascend to heaven, a belief that echoes the old Indian concept of reaching heaven by traveling upstream along certain rivers.[28]

In much of the Southern Hemisphere, the rainbow is viewed as a serpent. In Australian Aboriginal mythology, the rainbow is the primordial mother deity that gives birth to the totem animal-like ancestors of humans, who roamed the continent in "dream time" before sinking back into eternal slumber beneath the surface.

Some of the world's early civilizations arose on major rivers, such as in Egypt, Iraq, China, and the Indus Valley, while other early civilizations developed apart from major rivers, such as in Greece, Iran, Japan, Mesoamerica, and the Andes. This division obviously depends on particular geographical conditions. The riverine civilizations made use of the perennial water supply of the Nile, Tigris-Euphrates, Indus, and Huang He. Other Neolithic peoples invented schemes to harness river waters for irrigation. These civilizations developed ingenious means – such as surprisingly complex irrigation networks that terraced and distributed small streams – to harvest the much less abundant local water resources. This is evident in the long, underground canals (*qanat*) of Iran; in the sharing water schemes for rice agriculture in the Himalayan hills, the Philippines, Java, or Japan; or in the remarkable irrigation channels of Peru that have endured since the Incas. Along the Salt and Gila rivers of Arizona we find the massive irrigation schemes of the Hohokam civilization, abandoned around 1450 CE after some twenty-five years of drought (a similar drought-induced decline hit the Anasazi peoples of Northern Arizona).

In their mythologies, these varied civilizations all share a close link with the divine sources of water. An old Egyptian hymn addresses the Nile: "Greetings to you, O Waters that *Shu* [air] has brought . . . in which the earth [*Geb*] will bathe its limbs! Now hearts can lose their fear." The Nile spirit announces: "I am . . . the provider of the fields with plenty," to which the gods answer: "There was no happiness until you came down! . . . 'Canal of happiness' will be the name of this canal as it floods the fields with plenty."[29] A special god, *Hapy*, controlled the annual flooding of the River Nile, which is caused by rains in the Ethiopian Highlands.

Similarly, rain, flooding, and irrigation played various major roles in ancient Mesopotamia. Outside of Egypt, irrigation was necessary: rainfall and subsequent flooding was insufficient for agriculture.[30] Thus, Sumerian texts quote the major deity "*Enki*, the King of the Abzu [watery abyss]" who authoritatively states: "I am he who has been born as the first son of the holy *An* [one of the two leading deities] . . . When I approached high heaven a rain of prosperity poured out from heaven, when I approached the earth, there was a high flood."[31] Enki "filled the Tigris with fresh, life-giving water," and to make both rivers function, he appointed the god *Enbilulu* as "canal inspector."[32] The myth expresses this in striking terms: "He stood up proudly like a rampaging bull, he lifts his penis, ejaculates, filled the Tigris with sparkling water. . . . The water he brought is sparkling water, its 'wine' tastes sweet." And the texts rejoice: "the inundation of *Enlil* has come, the Land is restored."

In South Asia, the "river hymn" of the *Ṛgveda* praises the "three times seven" rivers of Eastern Afghanistan and the Punjab, but singles out the Indus River (*Sindhu*)[33] as the mightiest river: "ahead of all streams, the Sindhu overtakes them by his might"; it is "the best flowing one of the rivers, white-streamed."[34] All other rivers "rush towards it like mothers to their young, like cows," while the Sindhu "moves like a bellowing bull . . . its noise stretches across the earth up toward heaven."

This praise is in addition to that of the aforementioned half-mythical Sarasvatī. Her name signifies two rivers in Southern Afghanistan and in Eastern Punjab, now the Helmand (the ancient Haraxvaitī) and the almost disappeared Indian Sarsuti (*Ghagghar*). The Sarasvatī, too, is praised in the *Ṛgveda* as a mighty river, and is later on connected with the myth of the heavenly and mundane river *Gaṅgā* (Ganges). The heavenly Gaṅgā, the Milky Way, first fell on the Great God Śiva's head before reaching earth as the Ganges, which is depicted in a famous rock sculpture at Mahabalipuram in Southern India. Thus, just as the pilgrimage upstream the Sarasvatī leads to the world tree in the lower Himalayas – and from there to heaven – so, too, does the pilgrimage and bath during the *Kumbh Melā* at the Allahabad confluence of the Ganges and the Jamna (*Yamunā*), where the Sarasvatī – "flowing underground" from its disappearance in the deserts of Southwestern Punjab – joins them as the third "braid" (*triveṇī*).

In China, the Yellow River is regarded as potentially dangerous (like the Egyptian and Mesopotamian rivers), and it has justified its reputation as recently as the 1850s and 1930s, when it completely changed its course, leading to the deaths of millions. Thus, the fearsome river is the target of prayer. In Chinese origin myths, one of the major deeds of the second "emperor" *Nuwa*, an early mythical deity, was to kill the Black Dragon and to tame the river's flood waters.[35] Nuwa collected reed ashes and built river dams, letting the flood flow out through gorges to the eastern abyss.

Beyond Nuwa, there are a number of minor river goddesses in Chinese mythology, such as the goddess *Fufei*, the deity of the river Lo, along which the early capital Loyang was built.

In contrast to these riverine civilizations, the "desert religions," such as Zoroastrianism or Islam, extol the water of "life giving" springs and the resulting green oases. Around 1000 BCE, the monotheistic religion of Zarathustra (*Zaraϑuštra*) developed in the desert borderlands of Turkmenistan, Afghanistan, and Iran, in which there are only a few perennial rivers. Zoroaster's society was dominated by pastoralism, with some limited agriculture.[36] The later Zoroastrian texts (*Avesta*), which were largely composed in the arid lands of Bactria and Arachosia, are rightfully much concerned with water: they mention several deep, broad lakes[37] and rushing rivers[38] alongside the mythical rivers (*Ārəduuī*, *Daitiiā*) and lakes (*Vourukaša*, *Pūitika*, *Pišinah*). One Arachosian text gives a geographic account of the Helmand and the other rivers flowing into the lake Hamun; all of which could be used for irrigation.[39] The text warns, however, to look out for the sometimes devastating floods "at the end of winter" that can hit villages and spread through channels and underground canals.[40]

Islam, too, was first situated in the desert regions of Western Saudi Arabia, in a predominantly pastoral society with some trading towns, including Mecca and Medina. By definition, nomads look at oases and towns "from the outside," though they rely on their perennial springs for their animals. Thus, it is no wonder that the green of the oasis has become the favorite color of Islam, so much so that Muammar Gaddafi's Great Socialist People's Libyan Arab Jamahiriya chose an unadorned green rectangle for its national flag (Gaddafi also published his political theories in *The Green Book*); Saudi Arabia uses the same uniform green for its flag, adding only a sword and the Islamic declaration of faith.

Much of this is also found in the Hebrew Torah and the Christian Bible, with their frequent references to deserts and wastelands[41] and the search for water: for example, Moses's water miracle when the Israelites wandered in the Sinai desert for forty years,[42] or a recluse's stay in the desert (often of forty days): such as that of John the Baptist in the mountainous wilderness of Judea while baptizing people in the River Jordan, by Moses while fasting for forty days, or by Jesus who also fasted for forty days in the wilderness.[43]

In the myths of Sumer, Egypt, India, China, Japan, the Torah, and the Christian Bible, to those of modern populations across the globe, water is a central, critical force. As we have seen, this is in part due to the various individual ecological conditions encountered by the ancient civilizations, especially since the beginning of food production some ten thousand years ago. The early civilizations were in need of a reliable supply of water for their crops, by rain or irrigation, and hence stressed the importance of river or rainstorm deities. However, ready access to water was imperative even for our earliest human ancestors, and thus, water myths persevered through their descendants, whether hunter-gatherers or agriculturalists, all over the globe.

Water was and still is predominant in creation myths and their connected rituals, underlining the close relationship of mythological traditions with their immediate environment. While many of us today may not observe the same direct, spiritual connection with water, depending on our industrial water supply, we still worship water when we – as the great comic George Carlin used to say – satisfy the great American fetish of carrying with us our own water bottles wherever we go.

ENDNOTES

[1] *Ṛgveda* 10.129:3. The word *salila* clearly is related to the Indo-European word for *salt* – Latin *sal* – and thus indicates the primordial salty ocean.

[2] From the Babylonian creation hymn, "Enuma Elish"; see Mircea Eliade, *From Primitives to Zen* (New York: Harper & Row, 1977), 98; which has more recently been published as *Essential Sacred Writings from around the World* (San Francisco: Harper, 1992). Eliade's text is based on Ephraim Avigdor Speiser, "Akkadian Myths, Epics, and Legends," in *Ancient Near Eastern Texts Relating to the Old Testament*, ed. James B. Pritchard (Princeton, N.J.: Princeton University Press, 1950).

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[4] The word *elohīm*, clearly a plural, creates a problem, though this is disregarded in the standard Christian translations (or is explained away).

[5] Again the plural *elohīm*.

[6] Eliade, *Essential Sacred Writings from around the World*, 96.

[7] Paul Radin quoted in ibid., 83.

[8] Ibid., 88.

[9] See Michael Witzel, *The Origins of the World's Mythologies* (New York: Oxford University Press, 2012).

[10] Eliade, *Essential Sacred Writings from around the World*, 91.

[11] For a discussion of archetypes and diffusion see Witzel, *The Origins of the World's Mythologies*, 22 *sqq*.

[12] It would be interesting to see how many myths deal with real water bodies versus those that are thought to be truly mythological. However, such a statistical investigation is impossible for the time being since we only have partial myth indexes, such as Stith Thompson's effort of the 1930s or Yuri Berezkin's more comprehensive index, which appears mostly in Russian. See Yuri E. Berezkin, "World Mythology and Folklore: Thematic Classification and Areal Distribution of Motifs. Analytical Catalogue," http://ruthenia.ru/folklore/berezkin/eng.htm.

[13] For flowing and standing waters, see *Ṛgveda* 7.49:2: "The heavenly waters, or those that flow, those that have been dug, or that have been self-created . . . these divine waters shall protect me here!" Similarly, with the Prasun of Nuristan (Northeast Afghanistan); see G. Buddruss and A. Degener, *Materialien zur Prasun-Sprache des Afghanischen Hindukusch* (Cambridge, Mass.: Harvard Oriental Series 80, 2015), Text 24.

[14] The Indus was regarded as salty: it flows through the Salt Range of Northern Pakistan.

[15] See my blog Vedagya, "Kumbh Mela – Its Sources," http://vedagya.blogspot.com/2013/03/kumbh-mela-its-sources.html.

[16] For a full treatment, see Michael Witzel, "Sur le chemin du ciel," *Bulletin des Etudes indiennes* 2 (1984): 213–279, http://www.people.fas.harvard.edu/~witzel/CheminDuCiel.pdf.

[17] Purification with *earth* and water is mentioned by the eleventh-century poet-historian Kalhaṇa in his *Rājataraṅgiṇī* 6.69.

[18] Qur'an 5.5–6

[19] Hesiod, *Works and Days*, 725 *sqq*.; and Matthew 27:24.

[20] Numbers 8:7; and Exodus 30:17.

[21] See Gautama V. Vajracharya, “The Adaptation of Monsoonal Culture by Ṛgvedic Aryans: A Further Study of the Frog Hymn,” *Electronic Journal of Vedic Studies* 3 (2) (1997), http://www.ejvs.laurasianacademy.com/ejvs0302/ejvs0302.txt.

[22] *Ṛgveda* 7.103; 9.112:4.

[23] Bernhard Forssman, “Apaoša, der Gegner des Tištriia,” *Kuhn’s Zeitschrift* 82 (1968): 37 – 61.

[24] *Yašt* 8.31 – 33.

[25] My Own Market Narrative, “Well, They Practice Magical Thinking over Here Too,” July 14, 2012, http://myownmarketnarrative.blogspot.com/2012_07_08_archive.html.

[26] See the modern version at “Stories of Old; Creation,” http://www.maori.org.nz/korero.

[27] Wolfgang Münke, *Die klassische chinesische Mythologie* (Stuttgart: Klett, 1976), 86.

[28] In the Bible, however, the rainbow is the sign of God’s covenant with Noah after the great flood; with some Native American peoples, the rainbow is the web of a giant spider, woven to catch the sun, or it is the coat of the Great Spirit that covers rain.

[29] R. T. Rundle-Clark, *Myth and Symbol in Ancient Egypt* (London: Thames and Hudson, 1959), 100 and 102.

[30] This became even more important after the water level of the Euphrates and the Tigris fell considerably during the major climate reversal of the late twenty-first centuries BCE, and before it stabilized again during the seminal Ur III period.

[31] See “Enki and the World Order” in Eliade, *Essential Sacred Writings from around the World*, 22.

[32] Samual Noah Kramer, *The Sumerians: Their History, Culture, and Character* (Chicago: University of Chicago Press, 1963), 173, 179, 183.

[33] *Ṛgveda* 10.75.

[34] Ibid., 8.26.

[35] Lihui Yang and Deming An with Jessica Anderson Turner, *Handbook of Chinese Mythology* (Santa Barbara, Calif.: Clio, 2005), 11 and 105; and Münke, *Die klassische chinesische Mythologie*, 219 *sqq*.

[36] *Vīdēvdād* 3.23:30 *sqq*.

[37] “Caēcašta” in *Yašt* 9.21.

[38] *Yašt* 10.14.

[39] “Kąsaoiia” in *Yašt* 19.65 – 68.

[40] *Vōiγnā* or “inundation.” See *Vīdēvdād* 1.3; and *Yašt* 8.61, 8.56.

[41] See the Internet Sacred Text Archive, http://www.sacred-texts.com/bib/ebd/ebd102.htm.

[42] The mysterious number forty appears in several ancient traditions, including those of Iran and India; it may be linked to an astronomical feature: the forty days of the disappearance of the Pleiades. See Hesiod, *Works and Days*, trans. Hugh G. Evelyn-White (1914), 383 *sqq*., http://www.sacred-texts.com/cla/hesiod/works.htm; and discussion in Michael Witzel, “Jungavestisch apāxəδra- im System der avestischen Himmelsrichtungsbezeichnungen,” *Münchener Studien zur Sprachwissenschaft* (MSS) 30 (1972): 163 – 191.

[43] Matthew 3:1; Exodus 24:18; Exodus 34:28; Matthew 4:2.

Water Security in a Changing World

John Briscoe

Abstract: This essay defines the concept of water security and explores the implications of the eternal pursuit of it. I will describe how water security is perceived by wealthy and by poorer nations, the tensions that arise from these differing views, and how these tensions are being resolved in a world in which the geography of economics and power is changing rapidly. I outline a few iconic cases of how societies have built institutions and infrastructure to deal with both floods and droughts. The essay assesses the effects of changes in climate and land use systems, and the differing reactions to the new perception of "nonstationarity": the idea that these systems are less predictable than they have historically been. The essay concludes with some reflections on the challenges of educating young people seized with passion for the issues of their generation but who may have difficulty taking a long view of water security. Many have been taught about the environmental ravages wrought by water infrastructure, but few understand how these same infrastructure and institutions underpin the water security that the United States has achieved.[1] Similarly, we teach the next generation too little about the remarkable contributions of "thinking practitioners": experts who are also involved in policy-making and planning – whose work underpins the food, water, and energy security of their societies.

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The relationship of people to water is and has always been complex and contradictory. Ancient civilizations developed alongside rivers because of the services abundant and easily accessible water provided (such as irrigation, potable water, and transportation). Yet proximity to fickle rivers also meant that these civilizations were vulnerable to floods, droughts, and changing river courses. The challenge for civilizations both ancient and contemporary has been to confront this Faustian bargain and find balance – between too little and too much water on the one hand and between the financial and environmental costs and benefits of manipulating rivers, lakes, and aquifers on the other.

This essay addresses three contemporary aspects of this age-old quest. First, it describes what is meant by water security and outlines which aspects of water security keep forward-looking leaders awake at night. Second, the essay describes some successful efforts to manage the two ends of the water-security

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spectrum: droughts and floods. The essay concludes with some observations on the challenges that face policy-makers, scientists, and citizens in moving forward.

There are a few major concepts implicit in the idea of water security and its implementation challenges. First, water security is rooted in water's contribution to the "good life." An adequate supply of water of reasonable reliability and quality – for people, industry, agriculture, and energy – is essential for the well-being of societies. Second is the "Goldilocks" concept: that is, societies need just the right amount of water – not too little (few periods of scarcity) or too much (few periods of inundation). Third is the concept that building the institutions and infrastructure to provide water security involves financial and environmental tradeoffs. Fourth and finally is the idea that context matters: people and governments choose to situate themselves at different points on the "risk/cost curve" depending on levels of development and social values.

According to the vast outpourings of the catastrophe-prediction industry, there is no end to the list of risks that threaten civilization and society today. However, issues of water security have moved up the priority lists for even the most sober prognosticators; three examples are worth mentioning.

The first is the national security establishment. One decade ago, the cogitations of national security bodies were largely concerned with two issues: nuclear proliferation and terrorism. Today, there is broad agreement that a range of environmental issues constitutes a third strand and that water looms large in these concerns. For example, in 2012, the U.S. National Intelligence Council produced a major report on the global trends that would frame "the alternative worlds of 2030."[2] One of these four dominant global trends was the water-energy-food nexus, and the Council suggested that "water may become a more significant source of contention than energy or minerals . . . at both the intrastate and interstate levels."

The business community also expresses growing concern about water-related issues. Again, a decade ago, water would have been barely mentioned in the halls of Davos, the home of the World Economic Forum (WEF). The most recent WEF survey of global business leaders, however, shows that of the hundreds of identified risks to the global economy, not one has a higher combination of "likelihood" and "impact" than water.[3]

The third group expressing concern is citizens, as revealed in Globescan's annual surveys of citizens in Brazil, Canada, China, France, Germany, India, Indonesia, Mexico, Nigeria, Turkey, the United Kingdom, and the United States. For every year since 2008, "shortages of freshwater" have been the highest-ranked environmental concern, above water pollution, depletion of natural resources, air pollution, loss of biodiversity, climate change, and automobile emissions (in descending order according to the most recent poll).[4]

Perceptions about challenges are strikingly different among different groups of experts. As a former World Bank employee and as a university professor, I have been exposed to the perspective of elites in the most prosperous countries in the world (a group that economist Thomas Sowell has tellingly called "the anointed").[5] As part of the many talks I am privileged to give on water, I often give the (mostly highly educated and rich) audience members "clickers" to gauge their views on water-related problems and their solutions. These polls produce some telling results. People in rich countries believe that about 70 percent of people in the world do not have access to an adequate supply of drinking water, but in fact the proportion (as shown in the latest global survey conducted by UNICEF and the World Health Organization) is only 11 percent.[6] In terms of solutions, the vast majority of aid money going to water-related causes (from philanthropies including the Gates Foundation and thousands of smaller charities, and from aid agencies such as the World Bank and USAID) is used to "provide water to the unserved."[7]

While leaders in the developed world tend to view water as a matter of charity and an issue to be addressed only when it reaches the status of an emergency, leaders in the developing world have a sharply differing perspective. It is these leaders of the major "emerging markets" (such as China, Indonesia, India, Mexico, and Brazil) who have been responsible for the remarkable decline in poverty over the past twenty years (from global levels of over 50 percent to under 20 percent). As part of this broad-based progress, water services to the poor have improved dramatically. According to UNICEF/WHO figures, every day for the past twenty years over 280,000 people on average moved from "unserved" to "served."[8] While the leaders of the rapidly growing emerging-market countries are responsible for most of the global success in improved access to water, they see "water supply for the poor" as one element of a broad-based economic advancement program. They do not treat the social problem (as do "the anointed" in rich countries); they search for underlying economic solutions.

What challenges do developing countries face in providing reasonable levels of water security to their populations? First is the simple fact of the hydrological starting point. In the United States, for example, development started in the Northeast, where hydrology was favorable: not too much or too little rain; and abundant water for supply to factories and people, to dilute wastes, to generate cheap hydropower, and to transport goods to market cheaply via shipment on boats. Under such circumstances it was easy and cheap to build a water platform for economic and social growth. The financial capital accrued through this "easy hydrology" was subsequently used to finance the major works (such as the Hoover Dam) necessary to serve the parts of the country where hydrology was much less favorable. Similar processes drove the developmental history of most wealthy nations; a few figures give the general picture. Wealthy countries have developed over 80 percent of their economically viable hydroelectric potential; in arid areas (such as the Colorado River basin in the United States or Murray-Darling Basin in Australia) they have built reservoirs that can store about a thousand days of average flow to generate electricity and act as buffers against floods and droughts.[9]

The situation in developing countries is quite different. As a group, they often face far more challenging hydrological conditions than do now-wealthy countries: greater intra- and interannual variability and either too much or too little water.[10] And developing countries have invested far less in the water platform for growth. Compared to the 80-percent level of rich countries, Asia and Latin America have developed 30 percent of their viable hydropower respectively, and Africa has developed 10 percent. And compared to the thousand days' worth of water stored on the Colorado or Murray-Darling rivers, the reserves of water available in developing countries are much more paltry; for example, there is only a thirty-day supply of water stored on the Indus River in arid Pakistan.[11]

Fifty years ago, the primary mission of multilateral and bilateral aid agencies was to help poor countries build the water (and other) infrastructure deemed essential for growth. The rise of the environmental movement in rich countries, however, was accompanied by a rise in activism against the sorts of investments that had made rich countries rich. This was due in part to legitimate and important concerns with social and environmental impacts of large infrastructure projects. But it was also fueled by an ahistorical paradigm that scorned the same types of investments that had been necessary to bring about the privilege those critics enjoyed. Activist NGOs in the Northern hemisphere focused heavily and productively on the otherwise largely ignored business of aid. By the late 1990s, however, most of the agencies that had once funded water and other infrastructure in developing countries (including the World Bank and the bilateral agencies of the Unites States, Canada, and Europe) had withdrawn from this business.

This change created much tension on the boards of institutions like the World Bank, where emerging and poor countries protested about the hypocrisy of those who came to have water, food, and energy security in part because of major infrastructure and yet deny similar opportunities to countries in need. But as global economic geography has changed, so too have the politics of multilateral agencies and the suite of countries offering financial assistance. In 2003, the politics of withdrawal at the World Bank came to a head: a concerted effort led by China, Brazil, and India led to a turnaround in the form of a new World Bank water policy recognizing the strongly expressed needs of developing countries and committing itself to reengagement with "high-risk/high-reward" infrastructure.[12] Simultaneously, middle-income countries not only continued to invest heavily in their own major infrastructure, but became major funders of such infrastructure in the poorer parts of the developing world. The World Bank – even with the new policy and with increasing lending for infrastructure – finances just a handful of large dams around the world, whereas China finances hundreds outside its borders.

There is, then, a yawning gap between the understanding of the anointed in wealthy countries (who prescribe what others should do) and leaders in developing countries (who have to live with the consequences). While the former worry about the (rapidly declining) problem of the unserved poor and shy away from high-risk infrastructure projects, the latter focus on longer-term solutions: namely, building infrastructure and institutions for dealing with their (generally) difficult hydrology and the still-unconquered problem of national water security. Wen Jiabao, former Premier of China, worried that "water shortages . . . threaten the very survival of the Chinese nation," and Montek Ahluwalia, Minister of Planning for India, suggested that "India can envisage a solution to the energy problem, but we do not know how to solve the problem of providing the water we need for people, industry, and agriculture."

All successful efforts to enhance water security involve the simultaneous and integrated development of infrastructure and institutions, as the following two examples illustrate. The iconic contemporary case for addressing water scarcity is that of the Murray-Darling Basin in Southeast Australia. The core infrastructural foundation was built throughout the twentieth century, the end result being a system that used almost all of the available hydropower potential, and whose reservoirs could hold several years of water in storage. The core institutional foundation was laid in the 1980s as part of a more general push to restructure the Australian economy around the principle of competition. A core element of this restructuring was the separation of water rights from land rights, the conversion of existing water licenses into tradable rights, and the creation of a strong set of incentives to facilitate trade both within and between states. This system was put through a severe stress test by an unprecedented eight-year drought at the beginning of the new millennium, and it performed extraordinarily well. The core driver of this success was that water had quite different value in different end uses (low for rice, high for grapes and fruits, and high for cities and industry). As the supply of water fell, prices rose. For a rice farmer, it was now far more profitable to lease his water for a year to a high-water-value project than it was to grow rice in a drought. There were therefore massive, voluntary transfers between low-value and high-value agriculture and from the country to the city. Remarkably, the bottom line was that there was very little impact of gross value added in agriculture (let alone the economy as a whole) from a 70-percent reduction in water availability.[13] Several other promising examples of the use of markets in the Western United States are discussed in Terry Anderson's essay in this issue.[14]

An iconic case of addressing flooding comes from the lower Mississippi, where water collected over almost half of the land area of the United States is funneled down into the Gulf of Mexico through Mississippi and Louisiana. Following the founding of the Mississippi River Commission in 1879, there was a vigorous debate about how to avoid catastrophic flooding in the delta. Nature spoke in 1927 in the form of a huge flood. Once it became apparent that water could not be contained within the extensive levee system, dikes were breached to protect New Orleans (and other areas where privileged and influential people lived). The result was anarchy and widespread destruction, wreaked particularly on disenfranchised black communities.[15] This taught the United States some hard-learned lessons. Most fundamental, it was evident that in "the big flood" the Mississippi could not be contained within the levees, and so the philosophy of "making room for the river" was born. In a remarkable process of community consultation, engagement, and consensual decision-making, two special types of land areas were identified. *Floodways* function as alternative exits to the Gulf of Mexico when water volumes exceed the carrying capacity of the main stem of the river; and *backwaters* along the river can store water when the river is at a high stage, both replenishing aquifers and wetlands and catching and holding floodwaters, which are then released slowly after the flood crest has passed. Central to this process was 1) identifying areas that could occasionally be submerged without lasting economic or social impact (such as limiting development of infrastructure and housing in these areas); and 2) awarding ex-ante compensation to the owners of this land. The resulting Mississippi Rivers and Tributaries Project, financed by the federal government and managed by the U.S. Army Corps of Engineers, was built in an integrated fashion and largely completed over the subsequent eighty years. The great stress test came in 2011, when the valley experienced a flood of even greater magnitude than that of 1927. The outcome was an extraordinary triumph (all but ignored by the disaster-hungry media). All excess water went only to designated floodways and backwaters; the area flooded was 60 percent less than that of the flood of 1927; no major infrastructure was affected; and the implementation process was – with some exceptions – planned and consensual, thanks to often-brilliant consensus-building by the leadership of the Corps of Engineers.[16]

The broad lessons from these cases of drought and flood are similar: the need to walk on two legs (drawing on the support of both infrastructure and institutions); the importance of having a way to reveal the opportunity cost of a shortage or excess of water; the reliance on voluntary processes for reallocation of water; and the emphasis on avoiding government confiscation of land.

Finally, to those who live in the Murray-Darling or Mississippi basins, the above descriptions will appear to be Panglossian or naive despite these systems' success overall. In his study on the history of water and the state in Germany over four centuries, historian David Blackbourn shows how "final solutions" to the water problem are illusory: solutions are merely "provisional."[17] So it is, too, in the Murray-Darling and Mississippi, where major challenges continue to arise, either because they are actually new or because changed social values have given them new visibility. Australia is now negotiating a complex and much-contested process for determining an optimal balance between human benefit and environmental impact; and the Mississippi basin faces great challenges in maintaining an aging infrastructure while simultaneously addressing the challenges of coastal degradation (to which the dams and dikes contribute) and of the transport of phosphorus and other agrochemicals from the agricultural heartland into a large dead zone in the Gulf of Mexico.

The primary challenge of water security is and always has been dealing with the tails of the hydrograph (droughts and floods). What of the bold claim of a group of hydrologists that climate change means "the end of stationarity," or the end of our ability to accurately anticipate water-related events?[18]

First, it is true that hydrologists have long used often quite short "historic records" as substitutes for longer-term records on which they would prefer to base their planning. But hydrologists have also been clear that short records are still the best basis for long-term projections, regardless of their limitations. From the few existing long-term records and from reconstructed records (often based on measurements of tree rings), however, it has long been clear that climate has never been stationary, but subject to short- and long-term variability. The Colorado River is one interesting study. In the early twentieth century, the Colorado Compact based its allocations on one half-century of records of river flows, which suggested that there were about seventeen million acre feet of water to allocate. Flows in recent decades have been only about thirteen million acre feet. Paleontological reconstruction of seven hundred years of records shows that there have been many shifts in runoff patterns, and that, in fact, the unusual period is not the last hundred years, but the unusually wet half-century before the signing of the Compact.

Second, it is important to recognize that climate models are just that – models – and not reality, despite the seemingly precise maps and graphs they produce. My own engagement with detailed climate models of the Amazon shows that even the most credible models seldom produce credible data on critical variables (including basic realities such as the timing and distribution of rainfall).

Third, many changes beyond the climate are affecting the stationarity of water. For example, work I was involved in in the Paraná River in Brazil showed that land-use changes in recent decades not only have a much bigger effect than climate change, but also induce changes in the opposite direction from precipitation changes.[19]

Fourth, a single-minded focus on climate becomes counterproductive when it crowds out attention to both known variability and other sources of nonstationarity. For example, I have in recent years worked extensively in Pakistan, where devastating floods have always alternated with devastating droughts.[20] There is much uncertainty about the effects of climate change on the Himalayas, with recent data (from the Gravity Recovery and Climate Experiment satellites, for instance[21]) showing a far more nuanced view than the IPCC's claim in 2007 that "the glaciers will be gone by 2035" – an error that the organization corrected soon after it was made, but which nonetheless continues to circulate in the media and in public discourse in South Asia.[22] Pakistan is swamped with foreign experts pushing their own climate models, but the obvious need is to walk before trying to run: Pakistan must build the infrastructure and institutions necessary to deal with variability, starting with known variability and eventually expanding to plan for new sources of natural and human-induced changes. If Pakistan and its development partners were to follow this course while keeping a watching brief on climate science, it might more quickly remedy its tragic water insecurity.

The water glass, then, is both half-full and half-empty. As one privileged to be educating the next generation, I see reasons for both pessimism and hope. On the downside, young people who have grown up in a society with established water security (and the associated health, energy, and food security) are inundated with the politically correct but, in my opinion, mostly erroneous view that all water management in the United States has been a disaster. When they are exposed both to the reasoning behind water management decisions (for example, on the Mississippi) and to the challenges the future poses to water management, their response is rarely to reject that view but rather to ask, "How come no one shared that perspective with us before?"[23] Indeed, when I am able to engage students with thinking practitioners – experts involved in water-management policy – the students are surprised that hands-on managers are often doing quite well in much more complex environments than those addressed by academics and advocacy groups! Pleased as I am with this, I still encounter large numbers of students who want to work on water and climate change but show little interest in the maintenance of the crumbling infrastructure that underpins their own water security.

In the meantime, as though on another planet, the emerging economies of the world are working on creating the knowledge, institutions, and infrastructure to enhance their still-precarious water security. Since they live in societies in which the consequences of insecurity of water, energy, and food reflect recent national experience, theirs is a more pragmatic and clear-eyed view. Perhaps, in this changing world, it will be they who are able to define a new, more balanced engagement with the great challenge of building a water-secure world.

ENDNOTES

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Progress on Nonpoint Pollution: Barriers & Opportunities

Adena R. Rissman & Stephen R. Carpenter

Abstract: Nonpoint source pollution is the runoff of pollutants (including soil and nutrients) from agricultural, urban, and other lands (as opposed to point source pollution, which comes directly from one outlet). Many efforts have been made to combat both types of pollution, so why are we making so little progress in improving water quality by reducing runoff of soil and nutrients into lakes and rivers? This essay examines the challenges inherent in: 1) producing science to predict and assess nonpoint management and policy effectiveness; and 2) using science for management and policy-making. Barriers to demonstrating causality include few experimental designs, different spatial scales for behaviors and measured outcomes, and lags between when policies are enacted and when their effects are seen. Primary obstacles to using science as evidence in nonpoint policy include disagreements about values and preferences, disputes over validity of assumptions, and institutional barriers to reconciling the supply and demand for science. We will illustrate some of these challenges and present possible solutions using examples from the Yahara Watershed in Wisconsin. Overcoming the barriers to nonpoint-pollution prevention may require policy-makers to gain a better understanding of existing scientific knowledge and act to protect public values in the face of remaining scientific uncertainty.

Water is an important, dwindling resource. Water and aquatic ecosystems support industry, agriculture, outdoor recreation, aesthetic pleasure, aquatic food sources, and livelihoods. Massive, expensive efforts have been made to improve water quality and "repair what has been impaired."[1] These efforts have led to some important gains, but water quality is still poor in many rivers, lakes, and coastal oceans. Runoff of soil, nutrients, and other chemicals from agricultural, urban, and other lands is called nonpoint source pollution. In contrast, point source pollution comes directly from a pipe, such as at an industrial or municipal facility. Runoff of phosphorus – also called nonpoint phosphorus pollution – is a major cause of toxic algae blooms, oxygen depletion, and fish kills in streams, lakes, and reservoirs.[2] Why are we not making progress on nonpoint source pollution in water quality? What are the chal-

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lenges of producing science to predict and assess nonpoint management and policy effectiveness, and of using this science in management and political decisions? Finally, what changes are needed to improve water quality?

A major scientific enterprise is devoted to producing scientific knowledge to inform nonpoint policy and management through long-term monitoring, statistical analysis, and modeling. But is scientific knowledge actually reducing uncertainty about the causes of water-quality impairment and the effectiveness of control measures? Researchers are increasingly vocal about the challenges facing nonpoint-pollution science on sediment, phosphorus, nitrogen, and other pollutants.[3] For instance, it is well-established that end-of-pipe mitigation of phosphorus improves water quality, but proving the effectiveness of actions to control nonpoint-source phosphorus is challenging. It is extremely difficult to demonstrate causality when connecting water-quality conditions to policies and the behaviors of agricultural and urban residents. An increase in knowledge and data has therefore not always translated to more effective policy.

Once scientific knowledge is produced, why is it so difficult to use it as evidence in nonpoint pollution–related policy-making and management? Science does not determine public interests and values, but it can serve important purposes in policymaking and resource management.[4] It can identify problems, prioritize the location or type of interventions, identify the likely effects of actions before they are taken (including anticipating unintended effects), and evaluate the effects of actions after they are taken.[5] Science and society affect each other deeply.[6] It is important to understand how scientific evidence, models, uncertainty, and risk enter into the decisions of actors such as the Environmental Protection Agency (EPA), county conservationists, farmers, urban homeowners, and lake managers. We will illustrate how scientific information has been created and used to improve water quality in Wisconsin's Yahara Watershed, focusing on watershed nonpoint-pollution reduction and in-lake biomanipulation.

Water pollution is typically viewed as an externality that does not directly subtract from the productivity of those responsible for the pollution, except indirectly or through social limits. This means that producers of pollution are not inherently incentivized to remedy it; the issue of assigning responsibility becomes even more difficult with the diffuse nature of nonpoint source pollution. The difficult issue of nonpoint source pollution has led to a proliferation of blended regulatory, incentive, and collaborative efforts to engage homeowners, municipal stormwater systems, and farmers in reducing nutrient and sediment runoff.[7]

Building scientific evidence for nonpoint pollution is long, slow, and scale-dependent. Given the rapid changes taking place in ecological and social systems, is the baseline moving faster than we can learn? We suggest that, in addition to science, political will and public value should play a greater role in decision-making to improve environmental outcomes.

There are a number of difficulties inherent in producing knowledge about nonpoint-pollution control. First, a growing number of studies from around the world show that it is extremely difficult to determine the efficacy of interventions aiming to reduce nutrient runoff from watersheds. In many cases, freshwater quality has not been found to have recovered even after decades of nutrient management,[8] and the divergent explanations for lack of success reflect the complexity of watersheds as social-ecological systems.[9] Despite the urgent need for management interventions to protect freshwaters, there is a high level of uncertainty about the efficacy of methods; indeed, there may be fundamental limits to our knowledge of this subject. It is not clear whether watershed management is making progress on uncertainty; for now, the success or failure of policies may be a matter of luck rather than knowledge. For this reason, it is important to consider the barriers to the production of knowledge about nutrient policy and management and the opportunities to improve scientific understanding in this area. We will explore the reasons for the difficulty of demonstrating causal effects of nutrient-management policies in large watersheds, including: long time lags between intervention and response, spatial heterogeneity (that is, a solution that works in one site may not work in another), simultaneous changes in multiple pollution drivers, and lack of monitoring.

Nonpoint pollution–management programs involve large areas with multiple nutrient sources; many individual land managers; spatially heterogeneous topography, soils, and ecosystems; and diverse streams and lakes. Specific practices for ameliorating pollution – such as buffer strips, cover crops, tillage practices, and wetland restoration – are usually tested on relatively homogenous sites at scales of a few hectares for a few years. While these methods are effective in short-term, small-scale field trials, little is known about how they scale up to whole watersheds.[10] At the watershed scale, new sources or sinks for phosphorus and new interactions along flowpaths could emerge and lead to surprising outcomes. It is plausible that spatial interactions (such as movement of soil from one area to another) contribute to the observed failures of large-scale nonpoint-pollution management.

Interventions to mitigate nutrient inputs also have delayed effects because of the slow response of nutrients in the environment.[11] Time lags ranging from one to more than fifty years have been measured between the initiation of a management intervention and the observation of an environmental response.[12] Projections estimate that interventions to cut off phosphorus fertilization of soil will take two hundred and fifty years to produce a new, low-phosphorus equilibrium in the agricultural lands of a Wisconsin watershed.[13] In a diverse set of watersheds, response times for nutrient interventions ranged from less than one year to more than one thousand.[14] Such long time lags pose serious difficulties for scientific inference and for sustaining the engagement of the public and policy-makers.

Furthermore, many factors that affect water quality change simultaneously. For example, precipitation, land use, agricultural management practices, and ecological characteristics of lakes and streams are always changing.[15] Effects of management interventions to improve water quality must be discerned against this background of multiple changing drivers, each of which affects water quality. The lengthy response time of the environment compounds this difficulty. Ecosystem scientists generally employ an array of approaches, including observing paired reference ecosystems, to distinguish between the effect of the intervention and that of other changing drivers.[16] However, these tools of inference are rarely applied to nonpoint pollution–management programs.

Lack of monitoring is a common defect in nonpoint pollution–control programs. Without before-and-after observations of nutrient loads and water quality, it is impossible to determine an intervention's effectiveness in reducing nutrient runoff. Because of the previously mentioned long time lags, monitoring must be sustained for years or decades. The monitoring of nonpoint-pollution projects rarely employs reference watersheds, which are commonly used in ecosystem experiments. Reference ecosystems help separate the effects of other simultaneous changes from the effects of the intervention. Two neighboring watersheds, one mitigated and the other not, may have similar biogeochemical and hydrological characteristics and experience the same weather, but only the mitigated watershed should show effects of nutrient management. If it becomes clear the actions are working, then the reference watershed can also be managed.

Nonpoint control programs are sometimes evaluated by enumerating the number and size of conservation practices established instead of the nutrient characteristics of lakes and streams. While the number of conservation practices is important, reaching target nutrient loads and water quality is the ultimate goal. These metrics of water quality must be measured before and after the installation of the mitigation practices in order to evaluate the effects of the program.

How, then, should nonpoint pollution be addressed? Decision-makers and the public should expect slow responses and high uncertainty. Nonpoint-pollution management plans will be easier to explain if they include explicit plans for measuring and managing uncertainty. Sustained monitoring that includes measurements of nutrient outcomes is essential. Simultaneous monitoring of multiple subwatersheds (including a reference subwatershed) can reduce uncertainty by accounting for the effects of changes in weather, agricultural production, and development.

Policies for nonpoint-pollution management assume that outcomes will be predictable.[17] Models used for nonpoint-pollution planning tend to be complex computer programs with large numbers of parameters, often exceeding the number of observations from actual watersheds. Such models support a culture of spurious certainty that sets the stage for disappointment when freshwater ecosystem responses turn out to be slow, variable, and influenced by multiple changing forces. Instead, research is needed on the dynamics of uncertainty itself. For example, it would be helpful to observe unmanaged watersheds over the long term to understand how baselines are moving.[18] What is the frequency distribution of extreme nutrient loads and how is it changing? How can we best use landscape heterogeneity to understand multiple drivers through comparisons among subwatersheds? How can the planning process engage a broad cross-section of society, make the best use of science, and create realistic expectations about response time, variability, and uncertainty? Questions about the nature and management of uncertainty are moving to the foreground as society grapples with the expanding impact of nonpoint pollution on freshwaters.

How do management interventions affect complex systems such as lakes? Our ability to draw conclusions depends in part on experimental design and in part on how immediately the environment responds to a given change. During the 1970s, ecologists demonstrated that phosphorus pollution was the underlying cause of algae blooms in lakes.[19] In one key experiment, a lake was divided in half and enriched with carbon, nitrogen, and phosphorus on one side and only carbon and nitrogen on the other. Algae bloomed only on the side with phosphorus, clearly demonstrating the importance of managing phosphorous in lakes.[20]

In cases of point source–nutrient pollution, regulators can turn off the pollutant flow at the end of the pipe. In the celebrated case of Lake Washington, water quality dramatically improved in a short period of time after nutrient input from sewage was diverted.[21] The direct and immediate response of the ecosystem supported the belief that nutrient control was the cause of water quality improvements.

Wisconsin's Lake Mendota provides an opportunity to compare fast and slow responses to intervention and how they affect subsequent management decisions.[22] The lake's food web was manipulated by fish stocking and mortality to increase the abundance of *Daphnia pulicaria*, a highly effective grazer. The rise of *D. pulicaria* substantially improved water clarity in less than a year.[23] Previously, whole-lake experiments had compared manipulated and unmanipulated lakes and determined that food-web changes could improve water clarity.[24] Lake Mendota's sharp response to food-web manipulation corroborated these expectations.

In contrast, Lake Mendota's response to management of nonpoint phosphorus inputs has been quite slow.[25] There has been no statistically discernible change in lake water quality in more than thirty years, despite extensive efforts to mitigate nonpoint pollution entering the lake. Gradual changes in the watershed phosphorus budget have likely contributed to the lake's slow response.[26] Decades of management have been frustrated by simultaneous increases in manure concentration, precipitation, the number of large rainstorms, and impervious surface area.[27] These changes in phosphorus-pollution drivers, occurring simultaneously with changes in management practices, have allowed for conflicting interpretations of the effects of management on the lake. These interpretations are equally plausible, but each has starkly different implications for policy, complicating the jobs of managers and policy-makers.

Efforts to use scientific information as evidence to improve water quality face many challenges. Greater attention has been paid to the production of water quality science than to how that science is subsequently used as evidence in water-quality management and policy. Science has three primary roles in the formation of water-quality policy: 1) identifying and describing problems; 2) predicting the likely effects of potential choices; and 3) evaluating the effects of prior actions.[28] We will identify the barriers to using science in each of these three major arenas. First, underlying disagreements about public values and preferences influence how science is interpreted and used. Second, there are many disputes over the assumptions used to create models and the validity of their results. Institutional barriers such as complex regulatory environments can slow the uptake of new information.[29] In terms of solutions, individuals and organizations can learn and change their behavior or routines and social networks can enhance learning and quicken the diffusion of information.[30] Even if scientific information informs individual and organizational learning and management choices, it may not affect political decisions about funding or legal environmental protection.[31] Here we identify the roles that science plays in nonpoint policy and management, describe the barriers and opportunities for use of science in decision-making, and summarize the reasons it has been so difficult to reduce nonpoint source pollution.

The nature of nonpoint management itself presents challenges for policy and governance, in turn influencing the potential roles for scientific information.[32] Nearly all economic development and resource use – including primary production of food, fiber, and minerals and secondary processing into consumer goods and built infrastructure – produces some water pollution. Nonpoint-pollution sources are numerous and often well-organized, and each contributes only a small proportion of the pollution. Agricultural land use has a privileged status in environmental policy-making, which makes regulating agriculture difficult politically.[33] The beneficiaries of clean lakes and rivers for fishing, swimming, the habitat, and aesthetic pleasure are less cohesive, organized, and funded than pollution-producing industries, although business interests can also be powerful allies for clean water. In many ways, producers of pollution have a powerful sociopolitical presence, and this influences how scientific information is used for water-quality management.

Use of scientific information is one tool for improving decision-making, but science does not speak for itself. Scientific information becomes evidence in the minds and hands of actors with different positions, incentives, and viewpoints. The social-psychology theory of motivated reasoning suggests that people interpret information in light of existing beliefs.[34] At an organizational level, information that supports agency missions is more likely to be used – and also more likely to be funded in the first place – while other potential research is left undone.[35] Scaling up to whole watersheds, the diversity of stakeholder objectives and worldviews means that disagreements about the meaning of scientific information, such as modeled predictions, are inevitable.

Disagreements about values and goals often underlie disagreements about science in decision-making.[36] Once a goal has been established, scientific information can be used to help reach it. But if political actors are unable to agree upon values or goals, then the tendency is to shift the debate to technical disagreements over models and data sources.[37] However, it is not simple or realistic to wait to reach political agreement before beginning a modeling process to determine how to reach that goal, since both politics and scientific development are iterative, ongoing processes. Further, science influences goal-setting itself, since scientific information is often used to identify problems for action. Information about environmental conditions and trends must be translated into evidence of a problem if it is to inform a policy or management agenda.[38] Agenda-setting and problem identification are inherently sociopolitical processes that involve the framing and social construction of information.

Defining water-quality problems has been a long-term goal of water-quality monitoring and research. Water-quality laws, such as the Federal Water Pollution Control Act in the United States (the Clean Water Act, or CWA), established processes for setting water-quality standards for water bodies. The definition of how much pollution constitutes a problem depends on the uses of the water body in question; stakeholder-based definitions of water-quality problems vary widely. Typical indicators of water-quality problems include poor water clarity levels and high concentrations and total loads of sediment, bacteria, nutrients, and other chemicals in the water. Positive qualitative indicators such as fishability and swimmability (absence of algae blooms or fish kills) are also taken into account.

The voluminous data from water-quality monitoring does not by itself meaningfully inform water-quality management: these data must be interpreted and linked with public values in order for the science to be truly useful.[39] Monitoring schemes must be designed with the likely use of the information in mind so that their sampling is statistically relevant to those goals. Unfortunately, many large-scale monitoring efforts have not yielded information that fits the needs of managers and policy-makers. For instance, the EPA's Environmental Monitoring and Assessment Program (EMAP) struggled because it was viewed as out of touch with policy needs and exhibited a lack of consideration of how values drive information interpretation (despite warnings from the National Research Council and the Science Advisory Board).[40]

Predicting the likely effects of potential choices is also a challenge due to the limitations of models and prediction. As managers and policy-makers debate options, they rely on conceptual and quantitative models to make predictions about the intended and unintended results of alternative courses of action. Debates over the validity of model predictions are long-standing. In the nonpoint-source arena, models can estimate the sources of pollution, predict the efficacy of different types of solutions, prioritize spatial locations for management, and determine compliance with regulation.[41] Implementation often differs from modeled plans in unpredictable ways: for instance, reliance on voluntary farmer participation means that planners typically cannot predict or control where agricultural conservation practices will be applied.[42]

Models are widely misunderstood as "truth machines" in environmental policy.[43] Because models are often poorly constrained and sometimes have large and unclear errors, stakeholders are able to mount legitimate and significant challenges to the use and selection of models. Sometimes doubt is sown deliberately to discredit unfavorable data or model estimates.[44] But because models are better at estimating average conditions in a large area than assigning accurate estimates to particular parcels of land, individuals may be justified in their skepticism of the fit of models to their particular farms or residences. People generally have a tendency to think of their own situation as exceptional and to underestimate their risks compared to the average. As Carl Walters, a biologist and quantitative modeler, has concluded, "We cannot assure policy-makers that our models will give accurate predictions: they are incomplete representations of managed systems."[45] Critics suggest that models emphasize quantifiable over difficult-to-quantify objectives and shift the debate from values to technical terms.[46] To this end, environmental policy expert Daniel Sarewitz has written, "The abandonment of a political quest for definitive, predictive knowledge ought to encourage, or at least be compatible with, more modest, iterative, incremental approaches to decision making."[47]

Regardless of these shortcomings, models of nonpoint source pollution can and do play critical roles predicting the effects of incentive and regulatory programs. For instance, the Soil and Water Assessment Tool (SWAT) is a watershed-based model that was "developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, [and] land use and management conditions over long periods of time." SWAT is a "continuation of thirty years of nonpoint source modeling" that simulates the water, sediment, and nutrient balance at the land surface.[48] Water-quality regulations have necessitated these complex models for estimating point and nonpoint-source contributions to surface water pollution. In this case, the CWA prompted the Agricultural Research Service to develop the SWAT model in the early 1970s.[49]

Under the CWA, jurisdictions must develop a Total Maximum Daily Load (TMDL) for impaired waters: a calculation of the maximum amount of a pollutant that a water body can receive and still meet water-quality standards. As of 2014, sixty-eight thousand TMDLs had been developed in the United States. TMDLs and their implementation plans translate model results into responsibilities split among point sources and urban and rural nonpoint sources. For instance, SWAT provides the basis for allocating necessary reductions under the Rock River TMDL in Southern Wisconsin. In the Yahara Watershed, which flows into the Rock, modeling has contributed to goal setting, prioritization, and implementation.

In the Yahara Watershed, however, SWAT did not provide reliable estimates for phosphorus loads from agricultural subwatersheds when compared with measurements from U.S. Geological Survey streamgages.[50] SWAT substantially underpredicted agricultural phosphorus loading from agricultural subwatersheds, in part because it was not yet modeling late-winter runoff of manure and sediment on frozen ground. Farmers are also often skeptical of model results; a representative of the Wisconsin Farmers Union claimed that "landowner lack of trust in models" was a repeated issue. This mistrust is deepened by discrepancies between model estimates averaged over space and time and farmer experiences of individual fields.

Model limitations are becoming better recognized; some have suggested that their failure to predict measured outcomes makes SWAT and other similar soil erosion–based models "unsuitable for making management decisions."[51] SWAT and other models are based on techniques that have been minimally updated since the mid-1980s despite advances in understanding of soil phosphorus availability and transport, leading to a situation in which "the quality of commonly used models may now lag behind the demand for reliable predictions to make policy and management decisions."[52] However, analysis of model findings continues to reveal some of their limitations and lead to updates. Despite their imperfections, models are critical for regulatory policy and will continue to be used and improved in the absence of alternatives.

A third major role of science is to assess the effects of actions after they have been taken. Several barriers can impede assessment, including limited information, limits of causal inferences, and conflicting interpretations based on values and political preferences. After a course of action has been selected and implemented, long-term monitoring can indicate changes in conditions, but evaluations compared to a reference site are needed to make causal inferences about the effects of an action. Furthermore, information about "what works" often cannot be translated from one local context to another.[53]

One barrier to assessment is the fragmentary nature of water-quality data in the United States. The National Water Quality Inventory under the Clean Water Act requires states to report water quality assessment to the EPA. As of 2014, only 43 percent of lakes, 37 percent of estuaries, 28 percent of rivers, and 1 percent of wetlands had been assessed.[54]

In practice, the evaluation of compliance with new policies for enforcement purposes is typically based on behavioral changes, not on measured water-quality outcomes. Agencies often evaluate their effectiveness by relying on the same models that were used to predict the effects of interventions; therefore, if behaviors do not actually result in desired environmental changes, there would be no data to show this. However, a limited number of policy-makers are experimenting with performance-based management, which evaluates measured environmental outcomes rather than measurements of technology or behavioral changes (for example, edge-of-field monitoring on farms).

Evaluation is also a political process. Even when scientists demonstrate an effect (or lack thereof), it might not become the dominant narrative about a policy or program. Evaluations and performance information are constructed by actors to advance their interests.[55] For instance, organizations may promote their programs as successful even without substantial information about their effectiveness. Even the question of who has access to information is dependent on political and personal values. For instance, conservationists may wish to obtain farm- and field-scale information on soil phosphorus and land-use practices, but farmers may be reluctant to share those data, since they could be used to assign blame or intensify water-quality requirements.

Significant barriers face efforts to improve the use of science in decision-making. These include matching the supply and demand for science and communicating between the cultures and incentive-structures of scientists and managers.[56] Deeper issues challenge us to rethink how we use science. Perhaps we should not consider better use of science to be the ultimate objective, but rather better decisions.[57] Asking a question about better decision-making requires a normative view of what is socially desirable. Although in a broad sense, clean water, agricultural production, and thriving cities are all socially desirable, making tough decisions about trade-offs between these goals will require compromise and continual renegotiation. Social scientists examine the roles of science through multiple lenses, including discourse analysis of the social construction of information, psychological study of evidence and persuasion in decision-making, and systems models that examine the change in both social and ecological components of watersheds.

Organizational learning systems have been designed to advance the use of information in decision-making. Research on learning organizations examines how organizations learn and change their routines based on new information. Scenarios are one strategy that organizations can deploy to examine uncertainties and alternative future trajectories. Furthermore, organizations can learn about how to learn more effectively and develop new institutional structures and informal networks to facilitate learning.[58] However, efforts to build learning organizations may be impeded by institutional fragmentation; limited capacity; organizational culture; the different timelines and incentives of scientists, managers, and policy-makers; and the command-and-control paradigm (top-down management).

Nonpoint pollution challenges our ability to measure, predict, and regulate. Scientific information is limited by few experimental designs, complex causality, and the difficulty of creating solutions to fit heterogeneous spatial and temporal scales. Barriers to using the scientific information we *do* have arise in part from the conflict over values and goals for water and land use. Yet "thinking practitioners" have successfully improved water quality and used scientific knowledge to inform management, policy, and governance despite these many barriers.[59] There is no denying that science plays critical roles in goal-setting, planning, and evaluation. In the contentious process to extend Clean Water Act regulation to agricultural and urban nonpoint sources, models are cast in starring roles to prioritize implementation and assign responsibility. An examination of the use of science in management, policy-making, and governance reveals the coproduction of science, modeling, and nonpoint control systems. Overcoming the barriers to nonpoint-pollution prevention requires that stakeholders and policy-makers renew their commitment to learning from scientific information and at times act in the face of uncertainty.

ENDNOTES

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Water Unsustainability

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Abstract: Water is a vital renewable resource that is increasingly stressed by multiple and competing demands from people, industry, and agriculture. When water becomes unavailable or unusable, life itself cannot be sustained. Changes in supply and demand for water are driven by population growth, climate change, and our energy and land use choices. Poverty frequently precludes the ability of many people to respond and adapt to water insecurity. In this essay, we discuss the effects of these drivers on the diminution of rivers, aquifers, glaciers, and the severe pollution that renders some water resources unusable. While technologies for water reuse, desalination, aquifer replenishment, and better water pricing are important solutions, the recognition of water as a profoundly threatened resource and as a basic human right is essential for providing sustainable water for future generations.

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Water *unsustainability* is more easily understood than water *sustainability*: you know when you do not have it. When water is unavailable or when it is of unusably poor quality, life itself is unsustainable.

So how do we define water sustainability? Definitions usually involve the concept of long-term water availability for all uses. Supplying water to people for the duration of their lives is one definition, but is limited by a rather ethnocentric point of view. More broadly, we may define water sustainability as *the continual supply of clean water for human uses and for the use of all other living organisms*. This definition neither specifies exactly how much water is needed, nor does it require the unconstrained, infinite availability of water. Rather, it refers to a sufficient quantity of pure water for the foreseeable future for all biota, including humans.

Water is, after all, a renewable resource; sustaining its uses should be relatively easy. But in reality, we can have too much water or too little water at different times, and the water available may be of too poor quality. Water availability is often constrained by natural processes associated with the hydrologic cycle and geologic setting, or by jurisdictional boundaries of governmental authorities and

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water law. Water supply is also constrained by existing infrastructure to deliver available water. Our ability to ensure enough clean water for human uses is strongly influenced by the cost of water delivery and the price of and demand for water. Thus, many factors and trends affect the availability of water in space and time.

Because H_2O does not cross the boundaries of our atmosphere, either to or from outer space, Earth has held the same quantity of water for eons. Earth's hydrologic cycle is driven by the sun, which evaporates water from oceans, lakes, and streams, and causes vegetation to transpire water. Thus, water is in a continuous flux from evaporation to precipitation, resulting in the recycling, purification, and redistribution of it. However, the *quality* of water and the *fraction of* H_2O *in each water phase* (gaseous, liquid, solid) at a given location are subject to change.

Currently, more than 99 percent of all water on Earth is unavailable for human use because it is too saline (in the form of seawater) or is frozen as glaciers, ice, or snow. With a stored volume of about two million cubic miles, groundwater remains the largest component of freshwater available for humans. Lakes and streams represent the next largest stores at approximately thirty thousand cubic miles.[1] But the volume of freshwater stored in glaciers is diminishing as a warmer climate begins to melt continental glaciers and the Greenland and Antarctic ice sheets. Many changes in water quality and quantity are driven by human activities – not nature.

There are five "driving forces" of change that threaten water sustainability:

1) Population growth (and migration patterns to megacities). According to United Nations projections, the global population will expand from 7.1 billion to 9.2 billion by 2050, further diminishing the quantity of water available per person. Further, when millions of people migrate to megacities, it concentrates the demand and stresses local water supplies, again resulting in less water available per capita. Humans are also increasingly moving to coastal cities where seawater is too saline for drinking and desalinization is too expensive. As we pump freshwater aquifers more fervently to supply water for increasing population growth and urban development, salinity can intrude from the sea and despoil groundwater supplies.

2) Climate change (changing precipitation patterns and drought). Due to our shifting climate, dry areas are generally becoming dryer and wet areas are becoming wetter all around the world.[2] In arid areas, the relatively small amount of soil moisture evaporates quicker under hotter conditions, resulting in more frequent and profound droughts. Conversely, humid areas are becoming wetter with more intense precipitation events and floods: the warmer ocean evaporates more water, and a warmer atmosphere can hold more moisture, increasing clouds and bolstering global rainfall rates. Too little water and too much water are twin juggernauts of climate change that result in water unsustainability.[3]

3) Land use change (increasing agriculture, irrigation, and urban sprawl). Food and water are intimately connected. To feed an expanding global population, we employ increasingly intensive agriculture on expanded acreages, requiring more chemical inputs and further diminishing water quality. Runoff from agricultural land delivers soil particles, fertilizers, and pesticides into streams. Fertilizer nutrients, in turn, over-enrich coastal waters, causing eutrophication, harmful algal blooms, and hypoxia (low dissolved oxygen), which impairs water quality for humans and aquatic ecosystems alike.

Urban sprawl – which causes greater imperviousness, heightens stormwater runoff, and prevents infiltration to recharge aquifers – is shrinking groundwater supplies. Groundwater supplies are also diminished by the burgeoning water withdrawals demanded by expanding populations and global agriculture. Irrigation is by far the largest water user in the world. Its impact on aquifers and rivers is particularly acute because withdrawals are a "consumptive" use of water: the water is mostly lost to evaporation. In cases in which water is not entirely evaporated, agricultural return flows allow some reuse options, such as recharging aquifers through percolation (spreading) ponds. But often the return flows are of such poor quality (laden with salt or toxic leachates) that they are useless for groundwater recharge.

4) Energy choices (power production, biofuels, and unconventional extraction of oil and gas). Our energy choices to satisfy the needs of growing populations and development are loaded with water repercussions. For example, electric power production withdraws more water worldwide than any other use except irrigation. Fortunately, the cooling water from electric power plants can be returned to the receiving stream with less evaporative losses than irrigation. But if the temperature of the returned water is too hot, or if it contains anticorrosion chemicals or chlorine disinfectant, it may cause deleterious effects on downstream ecosystems and fisheries.

The so-called energy-water nexus describes this tension between developing energy and water supplies. It is axiomatic that one cannot have water without large energy inputs, or energy without significant water impacts. Development of new fossil fuels (natural gas, oil, and coal) may impact the quality of nearby surface and groundwater. Some energy development options extract considerably more water than others. "Unconventional" oil includes oil shales, oil sands, coal-to-liquids, gas-to-liquids, and deep-drilled ocean oil. Conventional oil drilling and processing uses about 8 – 20 gal/MMBTU (gallons of water per million BTU of energy produced), while unconventional development of oil sands uses significantly more: 27 – 68 gal/MMBTU according to Chesapeake Energy.[4] But the largest water user is irrigated corn used to produce ethanol biofuels, requiring more than 2500 gal/MMBTU, or roughly two hundred gallons of "virtual" water required to produce every gallon of ethanol fuel burned![5] That is in addition to the environmental impacts of fertilizers, eroded soil, and pesticides required for growing the feedstock.

"Unconventional" energy development affects water quality to a much greater extent than conventional drilling and processing. A blowout of a deep-ocean well, such as the BP Macondo Well at the Deepwater Horizon platform in 2010, causes an outright water-quality disaster. Approximately two hundred million gallons of crude oil spilled along the Gulf of Mexico coast directly into a sensitive fishery and a substantial tourism industry. Oil sands, another unconventional oil resource, require steam to liberate bitumen (a tar-like substance), resulting in discharge ponds of petroleum-contaminated water that both is harmful to wildlife and scars the landscape. Deep directional drilling and hydraulic fracturing for shale oil and gas deposits, which requires three to seven million gallons of water per well, are still other methods.[6] In hydraulic fracturing (popularly known as fracking), drillers inject a highly pressurized water, sand, and chemical solution into shale formations to fracture the rock and allow natural gas to flow more freely to the surface. The water solution, however, returns to the surface as flowback and produces water with extremely high salt concentrations and trace contaminants (toxic metals and radionuclides). Usually such flowback and produced waters are reinjected into deep wells, far below any aquifers used for water supply. Instead of deep-well injection, some oil and gas companies are trying to recycle this water for use in hydraulic fracturing at another well. But if it is left on the surface, the flowback and produced waters form ponds of exceedingly poor-quality water that are difficult to treat to an acceptable standard for discharge into receiving waters. Unfortunately, some unscrupulous gas companies abandon these ponds for others to clean-up or for nature to absorb.

5) Poverty (physical and economic water scarcity). Water scarcity afflicts poor people more gravely than those with resources to respond or adapt. Poor communities cannot migrate to a better location, pay to import safe drinking water, treat contaminated water to meet safe drinking standards, repair a dry well, or pump water across great distances. Volunteer foundations and nongovernmental organizations (NGOs) recognize this dire need and seek collaborative solutions. Goal 7 of the United Nations Millennium Development Goals – "Ensuring Environmental Sustainability" – seeks to reduce the proportion of people without access to safe drinking water by half between 2000 and 2015.[7] Indeed, the achievement of the safe drinking-water goal is a major success story of the UN program. Yet there remain eight hundred million people in the world who still do not have an adequate water supply; clearly much work remains. Nor has the related development goal of adequate sanitation facilities (toilets and conveyance of sewage) for the more than one billion people in need been met. The United Nations has adopted a post-2015 development agenda, with "Water and Sanitation for All" a stand-alone goal. Such a comprehensive global effort is absolutely essential for water sustainability.

All five drivers are highly interrelated. We cannot mitigate climate change without making the energy choices needed to transition out of the fossil fuel age. We must use land and energy wisely to help create jobs and raise people out of poverty. We cannot solve water problems related to urban sprawl without curbing population growth and migration to megacities. And we cannot ensure clean water for an expanding population without a global social agenda that builds strong communities and empowers them to meet future challenges.

Water unsustainability is becoming increasingly evident in impoverished countries, megacities, and large-scale arid regions. We see it in the water stress of the Middle East, North Africa, and South Asia. We see it in the investment of billions of dollars for water reclamation plants in Singapore and desalination plants in Tianjin, China, and San Diego, California. Every day, newspaper headlines attest to human struggles of having too little or too much water. We see it when lakes become so polluted that they can no longer be used for drinking, and when coastal waters turn into dead zones devoid of fish. We see it when water is no longer available for irrigating immensely valuable food crops, and when major cities are frequently flooded by storms. We see evidence in mudslides and wildfires, in one-hundred-year floods and five-hundred-year droughts. Let us now examine a few poignant examples of water unsustainability that have become all too familiar: rivers that no longer flow to the sea, wells that run dry, the extinction of glaciers, the loss of critical groundwater supplies, and economic water scarcity throughout the world.

The Colorado River is born from snowmelt in the Rocky Mountains of Colorado, Wyoming, and Utah. It twists through Nevada, Arizona, and California on its way to a final hurrah in Mexico, where it forms a twenty-four-mile borderline with the United States and travels seventy-five miles through Baja, Mexico, to discharge in the Gulf of California. The last remnant of freshwater flow is captured in Baja by the Morelos Dam, whose waters irrigate rich farmland in the Mexicali Valley.

But the Colorado River has experienced a steady decline in discharge volume over the past century; in most years since 1960, it has not even reached the Gulf of California. Dams, diversions, and irrigation have caused most of the water loss, including increasing withdrawals for an expanding population of forty million people living both inside and outside the Colorado River Basin. Millions of acres of expanded agriculture and the irrigation required to grow cash crops in the middle of the desert consume most of the incoming water.

Lake Mead is a main stem reservoir of the Colorado River near Las Vegas. It is the largest dammed water body in North America, though – as a victim of repeated droughts and rising withdrawals – it has not been full since 1983. It provides power for more than one million people and recreation for many more, but spreading the Colorado River over a large desert area has increased evaporative losses significantly. Since 2000, the surface of Lake Mead is down almost 130 feet, leaving a "bathtub ring" on the rocky catchment and divulging where water was once stored. Climate change has exacerbated evaporation from Lake Mead (and its upstream sister Lake Powell) and has decreased flow from the river upstream.

The Colorado River is not alone: the Indus River in Pakistan, the Yellow River in China, the Murray River in Australia, the Amu Darya River in Central Asia, and the Theertha River in India are just a few watersheds that terminate before reaching their destination. All are located in arid regions where temperatures and evaporation are increasing, and where excessive withdrawals of water for people and agriculture combine to promote water unsustainability.

Big Spring, Texas, doesn't spring anymore. The town lacks a big spring or even adequate surface water. Its wells have run dry and its residents face frequent drought and water shortages. In 2014, nearby towns Wichita Falls, Lubbock, and Amarillo, Texas, declared a stage five emergency for exceptional drought. It was the driest year on record – even drier than the Dust Bowl. Other towns in Kansas, Oklahoma, and Texas on the Ogallala Aquifer in the Southern High Plains of the United States have recently experienced "game changing" drought and overwithdrawals. That they all lie on the largest aquifer in North America turns out to offer them no insurance against drought. Although torrential rains and flooding in May 2015 finally broke the Texan drought, the need for innovative technology and investment in new water infrastructure had become clear to everyone.

Big Spring responded by building a $14 million treatment plant to treat wastewater and recycle two million gallons directly to nearby towns for drinking water. By June of 2014, the Wichita Falls water treatment plant followed suit and became just the second facility in the United States to practice *direct potable reuse* (DPR): the treatment of wastewater for direct reuse in drinking-water treatment plants without an environmental buffer. Texans never thought they would drink treated domestic sewage, but direct potable reuse is an increasingly common solution for water-short areas.

California had a near-record drought in 2008. That one broke, but the state has routinely been short of precipitation since

2011. Now, in 2015, about half the state is in exceptional drought (the most severe category) and virtually all of the state is abnormally dry. Governor Jerry Brown put mandatory restrictions on urban areas to curb water use, but 80 percent of the water in California is used by agriculture. Farmers have volunteered to reduce their consumption by 25 percent in an effort to prevent steeper mandatory cuts later on. In many parts of California, groundwater is all that remains, but in areas like Kern County near Bakersfield, it has been pumped-down by more than fifty feet since 2011. Fortunately, water is a renewable resource and nature stores freshwater in many places: aquifers, lakes, soils, glaciers, and snowpack. But in California, all are in short supply. Snowpack levels in the Sierra Nevada are less than 25 percent of normal levels, and reservoirs contain only a fraction of their capacity.

More broadly, the California drought is emblematic of a global problem: wells are simultaneously being depleted in Pakistan, India, Sub-Saharan Africa, China, and the Mediterranean region. Wells run dry through the interplay of excessive withdrawals for population growth, climate change, agriculture, industry, and energy projects. The combination of these drivers with widespread poverty inevitably causes water scarcity. Impoverished communities suffering from water scarcity cannot recover or adapt; they lack the "resiliency" to respond to the disruption of their water supply. Water may be available in the new market at a higher price, but many simply cannot pay.

Land-based glaciers are melting worldwide. And tropical glaciers are melting the fastest. In mountain ranges near the equator, tropical glaciers are our canaries in the coal mine, early warning agents of climate change. While it is true that glaciers have been melting ever since the Little Ice Age (circa 1650 to 1730), the melt rate is much faster now and has only accelerated since 1980. We are witnessing the demise of low-elevation tropical glaciers within our lifetime; it is not simply a climate change story but an important water supply story for this generation and the next.

Lower-elevation tropical glaciers tend to be smaller than high-mountain glaciers, and they are more vulnerable to melting. Loss of these glaciers means collapse of the communities that depend on glacial melt for water supply and irrigation of crops. In the Andes Mountains of Colombia, Bolivia, Peru, and Ecuador, glaciers below 17,700 feet are melting at the fastest rate in three hundred years: a near 3 percent loss per year. Since the 1970s, the glaciers have lost an average of four-and-a-half feet of ice thickness per year from a total of about one hundred thirty feet.[8] In two or three decades, they will be history.

On the way to extinction, melting glaciers provide a lifetime of service to people below. When glaciers first begin melting, melt-water rivers are bolstered and flow-rates increase. But once enough ice has melted, the river reaches a peak flow and flow-rates begin to decline. The seasonal timing of the melt may also vary, providing little water in late summer and fall, stressing irrigation and drinking-water supplies. At lower elevations, snowmelt and precipitation also provide water for rivers, and researchers strive to unravel the precise contribution of glacial melt to total river discharge. "Glaciers provide about 15 percent of the La Paz water supply throughout the year, increasing to about 27 percent during the dry season," Alvaro Soruco, an Andean researcher, has reported. A loss of 27 percent of stream discharge can be devastating to growing populations with increasing agricultural development.

In the Peruvian Andes, glaciers are melting so fast that this critical component of stream flow is vanishing. The Santa River flows northward along the base of the Andes, the Cordillera Blanca, and then turns west toward the seaport city of Chimbote. Precipitation in the Andes has changed little since 1970, but the coastal climate of Peru is about 0.7 degrees Fahrenheit warmer – enough of an increase to melt its glaciers. Santa River has already passed "peak discharge" from glacial melt, so future streamflow is expected to decline. Some river flow remains from local precipitation and groundwater inflow, but expanding withdrawals for irrigation projects in the coastal desert are claiming an ever-increasing share of this diminishing resource. During the arid month of July, only a trickle of water now makes its way down the Santa River to Chimbote, and a declining portion of that is glacial melt.

Lake Tai (Taihu) in Eastern China is the third largest lake in the nation. Near the mouth of the Yangtze River and the city of Wuxi, the lake has been celebrated for its beauty for centuries. Yet industrialization, agricultural expansion, and population growth have in recent years given Lake Tai the dubious distinction as having among the poorest lake-water quality in the world. In 2007, a harmful algal bloom of cyanobacteria (blue-green algae) choked the lake and threatened the water supply for over thirty million people. Since the 1990s, the Chinese government has taken a variety of drastic measures to combat the lake pollution, including closing dozens of industrial plants, flushing the lake with Yangtze River water, dredging contaminated sediments, and severely reducing the use of agricultural fertilizers in the basin. Authorities even controlled the price of bottled water when the price sky-rocketed due to exponential demand from a panicked public. But none of these interventions have been successful in restoring water quality, and Lake Tai remains a poster child of water unsustainability driven by the forces of population, expanding agriculture, and rampant industrialization.

By the time it flows from the Himalayas to the Bay of Bengal, the Ganges River in India serves approximately four hundred million people. But the Ganges is plagued by proliferate sewage pollution capable of contaminating whole river basins. According to the Indian government, of the eight hundred million gallons of sewage discharged daily along the Ganges River, only 20 percent receives any treatment whatsoever.[9] Yet every day two million people still bathe in the sacred river, posing a major risk for the spread of water-borne diseases. The Ganges is overloved and overused: she provides water for drinking and washing clothes, a receptacle for raw sewage and solid waste, and a final resting place for the ashes (and partial remains) of the thousands who are cremated on the Ganges annually in religious rituals. Clearly such practices render use of the river unsustainable, but huge investment in sewage treatment plants would be required to restore the sacred Ganges and protect the health of the Indian people who rely on it.

But it is not only underprivileged populations in developing countries who suffer from poor water quality. Rich countries have been polluting their water supplies with agricultural runoff from high-input agriculture and factory farms such as concentrated animal feeding operations. I was born and raised in Iowa, a prosperous state with the most productive agriculture in the world. Iowa rivers flow through immensely rich agricultural land, but farm runoff carries an insidious load of soil particles, fertilizers, and pesticides far in excess of what a healthy stream ecosystem requires. Further, nitrate from fertilizers moves easily from soil to stream via tile-line drainage systems. It is transported about eighteen hundred miles down the Mississippi River to the Gulf of Mexico, creating a coastal "dead zone" of low dissolved oxygen. This

Gulf Hypoxia is one of the largest of more than one hundred fifty such hypoxic zones around the world.

Increased agricultural activity to grow the feedstock to support a new biofuels industry also jeopardizes water sustainability in the United States. Biofuels are meant to provide energy security for developed countries and a high-value export for developing countries. But as an energy choice, biofuels are incredibly water intensive. Increased land and irrigation is required to grow the feedstock for biofuels (corn, canola, wheat, beets, and sugar cane for bioethanol; soybeans, sunflowers, and palm oil for biodiesel). In arid locations, large water withdrawals from aquifers are needed to irrigate crops, and more water is required at production facilities to produce the fuel. Fertilizers required to grow the feedstock crops lead to excessive nutrient runoff, which despoils water quality. At the same time, food prices may rise in response to the higher demand for corn, soybeans, wheat, and canola. In the United States at present, 40 percent of the corn crop (about thirty-six million acres of a total eighty-four million acres of corn crop) is dedicated to the production of ethanol biofuel. *Cellulosic* feedstock from perennial crops like switchgrass, miscanthus, and hybrid willow, or from crop and wood residues, hold promise for a greener future. Perennial crops do not require annual tillage and would reduce soil erosion; they would also use less fertilizers, pesticides, and irrigation water.

Physical water scarcity is defined as the lack of available water for humans and ecosystems, commonly occurring in arid areas, during droughts, and where water has been overallocated (causing unsustainable withdrawals). Economic water scarcity, on the other hand, is the lack of water infrastructure necessary to deliver water to people. It is typical of impoverished communities who cannot pay to access water from distant locations or whose water requires significant treatment for drinking. In individual families, it often falls to women and girls to find water wherever they can, including by traveling long distances to collect from wells or streams. Such sources may be contaminated, however, causing intestinal illness, especially in children.

Physical water scarcity presumes investment in infrastructure to overcome shortages during times of drought and in regions with progressively drier climates. Overallocation of water resources is common in California, where agriculture preceded other forms of development and "prior appropriation rights" dictate that farmers now control the water. When surface allocations are consumed during droughts, groundwater becomes the sole water supply and is quickly overdrawn. But the frequency and intensity of the problem is made direr by irrigation and by interbasin transfers to growing cities that may have purchased appropriative rights. The largest such transfer in recent years is the massive "south-to-north" interbasin transfer of water from the Yangtze River in China to northern megacities like Beijing and Tianjin. When the project is fully completed, it will transfer 4 to 5 percent of the annual flow of the Yangtze, the largest river in China.

Interbasin transfers may be avoided through water conservation and reuse, by recycling industrial and municipal wastewater (sewage) and treating it to drinking-water quality, and by practicing indirect or direct potable reuse. Industry is also contributing to water conservation by designing new plants with "zero water footprints" and by capturing the precipitation that falls on their property (rainwater harvesting) for treatment and recycling. But all of these measures require "getting the prices right" such that the cost of water reflects its scarcity in a free market. With higher prices, private and public water companies will develop the infrastructure necessary to conserve and reuse water and/or desalinate seawater and brackish groundwater. The cost will also incentivize citizens to learn to conserve water resources, as Californians have tried to do.

One solution to water unsustainability is to recycle treated wastewater for non-potable uses (such as using purple pipes for watering lawns and shrubs) or to practice water reuse by recycling highly treated wastewater for use as drinking water. Water reuse is actually widely practiced today, if inadvertently. By the time the Trinity River in Texas flows from Dallas–Fort Worth to Houston, every drop has passed through a wastewater treatment plant. Withdrawals from the river for drinking-water treatment and distribution use treated domestic sewage whether customers realize it or not. Because of vast improvements in wastewater treatment practices, the Trinity River is of surprisingly good quality and still supports many aquatic species. Thus, people already practice potable water reuse in one of three forms: 1) inadvertent potable reuse (as in Trinity River, Texas); 2) indirect potable reuse (as in Orange County, California); and 3) direct potable reuse (as in Big Spring and Wichita Falls, Texas).

Indirect potable reuse is the practice of reusing highly treated effluent from domestic or industrial wastewater and discharging it into a reservoir or aquifer (an environmental buffer) for storage. After a few months, the water is withdrawn and treated for drinking-water distribution. The environmental buffer tends to help users overcome the "yuck factor" that typically characterizes public opinion on drinking highly treated sewage (direct potable reuse). In indirect potable reuse, three factors are at play. First, the waters are mixed (diluted) with existing water in the reservoir or aquifer. Second, the treated wastewater is naturally filtered and purified in the reservoir or aquifer for some period of time. Finally, after the water is withdrawn it is treated once again to drinking-water standards prior to distribution.

There are only a few communities in the world that presently practice direct potable reuse of drinking water. The first use of direct potable reuse was in Windhoek, Namibia, in 1968, when 250,000 people began using highly treated wastewater for drinking. Windhoek has practiced direct potable reuse ever since with no reports of illness or long-term negative effects. Big Spring, Texas, is the first application of this process in the United States, and its success has led Wichita Falls, Texas, to follow suit.

One of the most urgent tasks for communities facing water unsustainability is to replenish their depleted aquifers. Sustainable groundwater levels offer a measure of resiliency for the future akin to water insurance. Full aquifers, reservoirs, and storage tanks all offer insurance in times of need, but aquifers are immense and – better than any other method of storage – can protect and hold more water with little loss to evaporation.

Aquifer storage and recovery (ASR) and shallow aquifer recharge (SAR) are two methods practiced today in Oregon, Washington, Nevada, California, Florida, and Texas. Shallow aquifer recharge refers to the percolation of water from a surface pond to replenish a shallow aquifer, though not necessarily for recovery and drinking-water reuse. Full aquifers are desirable themselves for the capacity to bolster streams and to restore wetlands and springs that may have drained.

California's Orange County Water District Groundwater Replenishment System (GWRS) is a leader in shallow aquifer recharge. It recycles and treats wastewater that would have otherwise been discharged to the Pacific Ocean. The wastewater is treated to very high purity and exceeds state and federal drinking-water requirements; but rather than be withdrawn for drinking, the treated wastewater is naturally filtered through sand and gravel percolation basins in Anaheim, California. There the replenished aquifer serves as the source of drinking water for 2.4 million people. The groundwater is subsequently pumped-up, treated again, and distributed to nineteen municipal water agencies.

Aquifer storage and recovery describes the process of using wells to pump water into confined aquifers under pressure below the water table (where the water pressure head equals the atmospheric pressure). These aquifers may often be brackish or slightly salty, and the fresh, highly treated wastewater forms a "bubble" on top of the aquifer that can be accessed during a drought or dry season as an emergency water supply. The South Florida Water Management District oversees the operation of dozens of injection wells with the capacity to recharge aquifers with water of various qualities, including treated and untreated groundwater, partially treated surface water, and reclaimed (highly treated) wastewater.

In this essay we have seen that driving forces of population growth, climate change, urban and agricultural sprawl, energy development, and global poverty jeopardize future water supplies and render our present practices unsustainable. Water unsustainability poses risk for this and future generations. We should adapt to these changing conditions and mitigate them wherever and whenever we can. Adaptation takes the form of preparing for climate change, creating and refurbishing our water infrastructure, reusing water, recharging aquifers, making wise energy choices, and utilizing hyper-efficient irrigation for crops to feed the world. Mitigation requires transitioning from the fossil fuel age and improving human prospects through acts of global cooperation, as in the United Nations Sustainable Development Goals post-2015.

Many of the problems discussed herein will not be solved solely through new technologies. Economic and social issues are integrally linked to the problems of water sustainability. For example, we will not come to grips with economic water scarcity without the determined efforts of all stakeholders to eradicate poverty, improve education, and empower communities.

We are today experiencing a widespread crisis of water unsustainability throughout the world, with effects at the local, regional, and global scales. At the local scale, the drivers cause profound hurdles for individuals and families in gaining access to safe drinking water. At the regional scale, droughts and floods are increasingly frequent, inflicting human misery on a burgeoning population, while ecosystems suffer from poor water quality caused by our energy and agricultural practices. At the global scale, our efforts to reduce our greenhouse gas emissions have been stymied by competing economic and political interests. It is likely we will come to know the impacts of climate change through the effects delivered upon our most vulnerable and shifting water resources. Unless we can overcome or adapt to these driving forces, future generations will inherit a legacy of declining and degraded water resources. Our relationship with water and how we use it can evolve to meet this challenge, but it requires an understanding of the drivers of unsustainability and an acceptance of high-quality water as a human right.

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Adaptation in the Water Sector: Science & Institutions

Katharine L. Jacobs & Lester Snow

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ENDNOTES

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Urban Water-Supply Reinvention

Richard G. Luthy & David L. Sedlak

Abstract: Cities in drought-prone regions of the American West and Australia provide examples of innovative approaches to utilizing local water resources to achieve more resilient water supplies. Geographical realities, population growth, and favorable economic conditions can create the impetus for investments in new technologies, while support by activist groups and NGOs can encourage more sustainable approaches using locally sourced water. New approaches – whether desalination, stormwater use, water recycling, or potable reuse – share a common path to mass adoption. After a period of piloting and demonstration-scale projects, water providers with few options become early adopters of new technologies. And after the early adopters have gained experience and have used it to support the new approaches, the costs and risks of failure decrease for other providers. Thus, a wider cross section can adopt the new approach. The pioneering projects described herein are the first stage of the reinvention of our urban water systems.

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The solution to the challenge of urban water security will likely consist of a combination of demand management and the development of a portfolio of new water supplies. For reasons described in this essay – in addition to competing demands for imported water and the impacts of climate change on the hydrologic cycle – it is likely that new water supplies will rely on a mixture of localized strategies such as desalination, urban stormwater capture, and water recycling. To gain insight into the factors influencing the process through which cities pursue new forms of local water supply, and to identify policies that can be used to encourage the transition to more resilient urban water supplies, it is instructive to consider four specific technologies – desalination, stormwater use, water recycling, and potable water reuse – and the preconditions that have led cities to adopt different solutions. With respect to the development of urban water systems, local conditions play a major role in the decision-making process. Nonetheless, some common themes are evident among the early adopters of urban water-supply reinvention and water reuse. For example, rapid population growth coupled with favorable economic conditions

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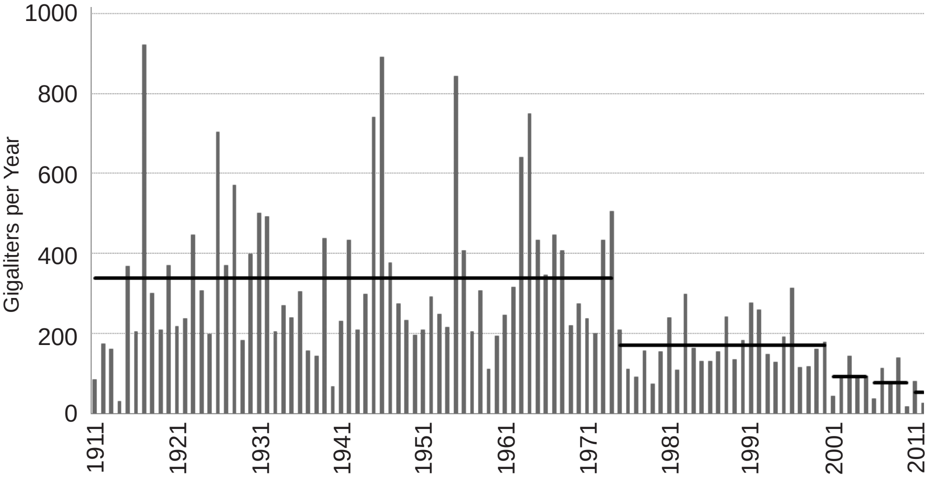
can create an imperative for responding to water stress through investment in new water-supply technologies, rather than by imposing growth restrictions or expecting further gains once demand-management solutions are in place (such as mandates for specific types of landscaping or changes in plumbing codes). In addition, the concerns of activist groups and NGOs, the ability to develop alternative supplies (as opposed to limiting choices), local geographic constraints, and water quality concerns – particularly with respect to salt management – all play an important role in the selection of the specific technologies used in decisions about future water supplies.

Australia is the driest inhabited continent; and its population is concentrated in urban areas along the coast. Australia has experienced many droughts, but the most severe drought since British settlement was what came to be known as the *millennium drought*, which lasted from approximately 1997 to 2009. The millennium drought altered public opinion about climate change and water-use behavior, and energized governments to take swift action to "drought-proof" their water supplies.[1] In what is described as one of the most dramatic and swiftest water infrastructure transitions ever undertaken,[2] Australia's five major metropolitan areas (Sydney, Melbourne, Brisbane, Perth, and Adelaide) embraced seawater desalination to augment drinking-water supplies and commenced on a rapid five-year infrastructure construction program.

Perth is a case study of the key factors that influence the choice of desalination: permanent decline in rainfall, technological developments, and cost reductions in desalination technology and sustainability considerations. Located in Western Australia, Perth is a very dry city, and 2001 was its driest year on record. Perth was among the first regions to feel the impact of climate change and to confirm the belief that climate change had altered the hydrologic cycle. Figure 1 shows what was unique about Perth: permanently reduced step-down average inflow to its catchments that became apparent in 1975.[3] The permanently reduced water supply for Perth resulted in planning for desalination prior to the millennium drought; desalination was the insurance against a worsening situation. At the time of its completion in 2006, the Perth Seawater Desalination Plant in Kwinana was the first large desalination plant of its kind in Australia, and it now provides about 17 percent of Perth's water supply. The clear step-down in Perth's water inflow over three decades from 1971 to 2001 was not mirrored by Eastern Australian cities like Melbourne and Sydney until the millennium drought, and even then it was not sustained after the major rains that followed the drought. Thus, hindsight supports the scale and urgency in Perth's desalination decisions; less so for the cities in Eastern Australia, where potential water sources and management alternatives are more diverse and where public support favors more smartly used grids, stormwater harvesting, and wastewater recycling.[4]

The second factor is that, over the past forty years, seawater desalination costs have greatly declined. Advances in reverse osmosis technology – in which seawater is pressurized against a semipermeable membrane that allows diffusion of water but holds back the salts – are more cost-effective today than older thermal distillation systems. The amount of power required to treat one cubic meter of seawater has declined steadily due to technological improvements in more permeable membranes, energy recovery devices, and more efficient pumps. The energy required for the reverse osmosis step has decreased nearly eight-fold since 1970.[5] The timely advances in reverse osmosis systems reliability and the power and cost efficiencies

Figure 1
Historical Decline in Yearly Inflows into Perth's Dams



Source: Western Australia Water Corporation, *Water Forever, Whatever the Weather: Drought-Proofing Perth* (Leederville, Perth: Water Corporation, 2011). Figure updated with permission.

clearly influenced Perth's decision to embrace this technology.

A third factor in Perth's decision to desalinate water was sustainability considerations. Environmentalists were opposed to using coal-fired plants to power the desalination plants and thus pressured the Water Corporation to find a nonpolluting, renewable power source.[6] The result was a partnership with a regional power company to build an eighty-megawatt wind farm at Emu Downs, two hundred kilometers north of Perth. Two-thirds of the wind farm's production would power the Kwinana desalination plant. Continuing this trend, the Water Corporation purchased renewable energy from solar and wind farms to power a second desalination facility: the Southern Seawater Desalination Plant in Binningup, south of Perth. Australia is the first country to link desalination with renewable energy.[7]

In short, desalination was the option of last resort for a desperate Perth and two desalination facilities now deliver almost half of Perth's water-supply needs.[8] Spain and Israel have followed Perth's lead and have similarly chosen desalination to boost their water supply.[9]

Los Angeles, along with many cities in California, was built with imported water. Beginning early in the twentieth century, massive water infrastructure investments – from cities, the state, and the federal government – led to the creation of a vast network of reservoirs, dams, and aqueducts that supported California's stunning population growth and booming economy. However, by the beginning of the twenty-first century, it was apparent that California's metropolitan regions had reached their limits in terms of reliance on imported water. The City of Los Angeles provides a model of how a major policy change at the municipal level can achieve a more sustainable and reliable water supply.

In 2007, the situation in Los Angeles reached a crisis: it was the driest year on record for the city and the lowest snowpack on record in the Eastern Sierras, from which the city receives a major portion of its water supply. Continued population growth and uncertain climate change impacts put additional stresses on the water-supply system. Meanwhile, court rulings invoking the Endangered Species Act led to reduced exports from the Northern Sacramento–San Joaquin Delta southward to Los Angeles via the California aqueduct. Court actions enforcing the state's public trust doctrine also mandated less flow to the Los Angeles aqueduct, requiring more water for environmental mitigation and enhancements in Mono Lake and the Owens Valley in the city's Sierra Nevada catchments.

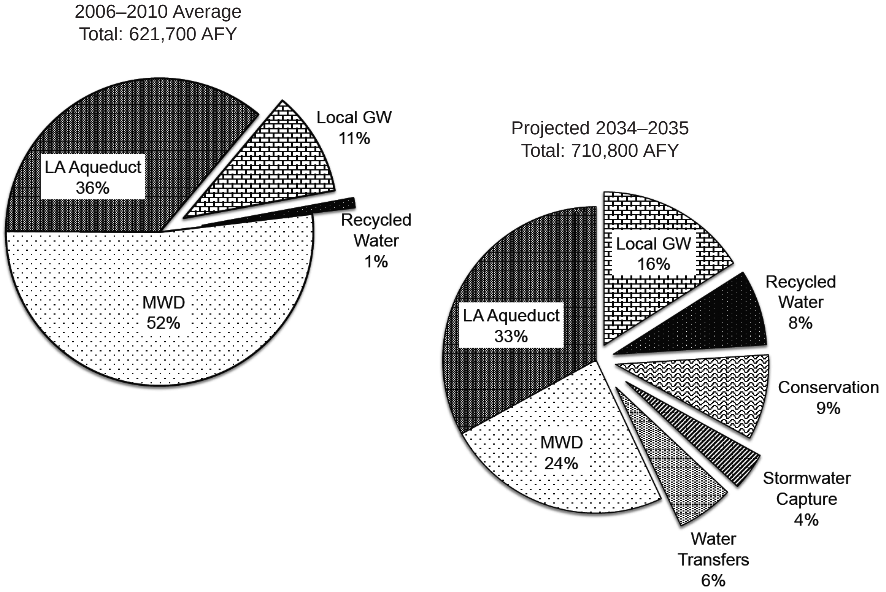
The convergence of these factors caused Mayor Antonio Villariagosa and the Los Angeles Department of Water and Power (LADWP) to embark on a new course of creating sustainable sources of water for Los Angeles. This landmark blueprint for action, described in the document *Securing L.A.'s Water Supply*,[10] seeks to reduce reliance on imported water and meet all new demand through conservation and expansion of water recycling, stormwater capture, and groundwater cleanup and storage.

Figure 2 shows two pie charts that describe the makeup of Los Angeles' water supply today and what it will look like in 2035 in acre-feet per year (AFY; one acre-foot is about 0.32 million gallons or 1,200 cubic meters).[11] Note the reduction in reliance on imported water from the Metropolitan Water District (MWD), which is the major wholesaler for water supplied from California's State Water Project and the Colorado River aqueduct. Today, the Metropolitan Water District supplies about one-half of Los Angeles' water. In twenty years, this will decrease by 50 percent in absolute terms despite continued population growth. This is achieved by increasing the water-supply portfolio, especially through development of local sustainable water supplies.

As depicted in Figure 2, LADWP's future water-supply portfolio does not include seawater desalination. This is a result of concerns about costs and the environmental impacts – raised by local activist environmental groups in Southern California – associated with desalination.[12] For example, the Surfrider Foundation has voiced concern about open-ocean intakes, advocating instead for subsurface intakes to prevent harm to marine life, and has pointed out that concentrated brine discharge can degrade marine habitat if not properly diluted. The Sierra Club has raised these same concerns, adding questions about the energy intensity and increased greenhouse gas emissions associated with seawater desalination. In short, the cost, environmental impacts, and unpopularity of desalination with the public and NGOs – and the ready availability of alternatives – led the city and the LADWP to meet the city's future water-supply needs through conservation and significantly enhanced stormwater capture and water recycling.

As Figure 2 illustrates, Los Angeles aims to reduce water demand by 64,000 AFY by 2035, which is in addition to the 100,000 AFY already conserved since the 1990s. From 1980 to 1990, population grew at 1.7 percent per year, with water demand growing at the same rate. But after the LADWP began implementing water conservation measures in 1991, demand has remained flat despite a population growth of 1.1 million people. From 2010 to 2035, Los Angeles' population is projected to increase by 367,300 persons, and the city's conservation goal is to reduce per capita water use

Figure 2
Comparison of Existing and Projected Water Supply Sources for the City of Los Angeles



GW: Groundwater. MWD: Metropolitan Water District. The charts do not reflect the 100,000 acre-feet per year (AFY) of existing conservation. One acre-foot is about 0.32 million gallons or 1,200 cubic meters. Source: Los Angeles Department of Water and Power, *2010 Urban Water Management Plan* (Los Angeles: Los Angeles Department of Water and Power, 2010; rev. 2011).

to 138 gallons per person per day by 2020.[13] Thus, with aggressive water conservation, the amount of water needed for an additional 367,300 persons is about 57,000 AFY. This illustrates that water conservation can reduce the future increase in demand for water caused by population growth, but conservation does not significantly reduce the overall demand for imported water. Clearly, aggressive conservation can accomplish much. But after low-flow devices are installed in new and older buildings, plumbing codes are changed, and incentive programs are implemented for landscaping conservation, there is not much more that can be done using existing conservation techniques. For these reasons, stormwater capture and water recycling play critical roles in reducing overall water imports for Los Angeles.

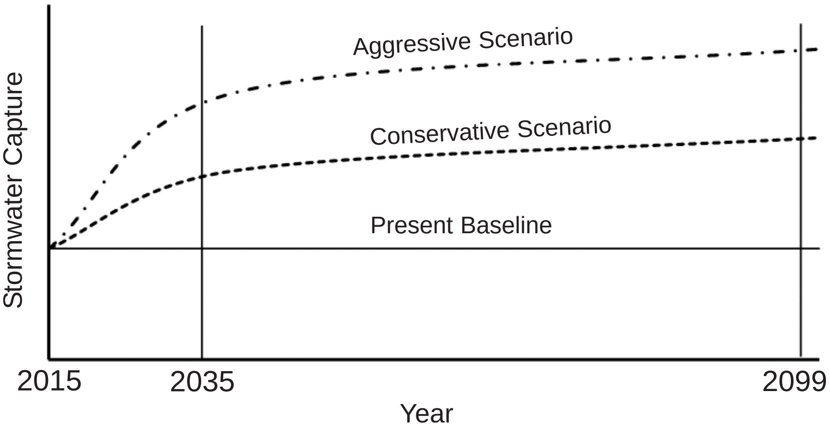
Work is now underway to upgrade and construct centralized projects for stormwater capture and groundwater recharge (the hydrologic process through which surface water becomes groundwater) to increase capture/recharge productivity by at least 25,000 AFY by 2035. An additional 10,000 AFY of conservation is expected to result from decentralized systems like rain barrels and neighborhood-scale cisterns. To achieve these goals by 2035, the LADWP created the Watershed Management Group, a partnership among agencies and environmental groups (including TreePeople and the Green LA Coalition) responsible for developing and coordinating stormwater projects among stakeholders. The Watershed Management Group's primary purpose is to enhance Los Angeles' water supply by increasing stormwater capture at existing centralized facilities and promoting distributed stormwater infiltration systems.[14] Stormwater capture is popular with environmental groups and NGOs because, in addition to groundwater recharge, capture leads to the creation of green space and reduction of pollution load at beach sites.

Los Angeles has captured stormwater for over eighty years in the San Fernando Basin through the flood plains and tributaries of the Los Angeles River. But urbanization increased the city's hardscape, resulting in less infiltration of stormwater and a decrease in regional groundwater storage. Los Angeles is currently developing a stormwater capture master plan to determine stormwater capture potential, feasible locations for centralized and decentralized stormwater capture systems, and costs and milestones.

The low-lying flatlands of Los Angeles are not adjacent to large tributaries. In these areas, distributed, smaller stormwater infiltration strategies will be implemented at the neighborhood scale and the scale of landscape changes on individual citizens' property. Because of its permeable soils, the San Fernando Basin provides the best locations for new and enhanced facilities for large-scale stormwater capture. Figure 3 shows an estimate of the twenty-first-century stormwater capture potential for Los Angeles under two scenarios: 1) an aggressive path with nearly 150,000 AFY captured in centralized facilities and 44,000 AFY captured in decentralized facilities; and 2) a more conservative path with modest increases beyond the 2035 goals outlined above.[15] Although theoretical, the curves shown in Figure 3 are based on specific projects implemented at the land-use level. The conservative approach assumes that stormwater capture is limited to areas with no contamination, while the aggressive-action scenario assumes that groundwater contamination is no longer an issue. The long-term potential for upgraded and new centralized facilities for stormwater capture and recharge would significantly change the water-supply portfolio shown in Figure 2. But uncertainty in how to safely capture, treat, and recharge stormwater in ways that protect groundwater quality, provide community benefits, and gain the support of activist groups and NGOs remains a significant challenge to achieving these ambitious goals.

Enhanced water recycling is expected to grow eight-fold by 2035. Los Angeles also has a history of using recycled water for parks, golf courses, and cemeteries. Recycled water is currently in use at the Los Angeles Japanese Tea Garden, Wildlife Lake, and Balboa Lake, after which water continues to flow to the Los Angeles River, where it supports native plants and wildlife. Recycled water is also injected into the ground near the coast to prevent seawater intrusion into local aquifers (underground layers of rock through which water can flow, and from which water can be drawn using a well). *The Urban Water Management Plan* calls for expanding the recycled water pipeline system and using recycled water for groundwater replenishment. Recycled water pipeline systems are expensive to install and often are the major obstacle for expanding water reuse beyond areas adjacent to a centralized treatment plant.[16] Los Angeles' solution is to expand the recycled water distribution system for nonpotable uses for major consumers like parks, lakes, refineries, and generating stations. Groundwater replenishment with recycled water is also an objective, but this requires advanced treatment, as is explained below. For groundwater replenishment with recycled water,

Figure 3
Illustration of the Potential for Stormwater Capture and Recharge to Provide More Reliable and Sustainable Water Supplies for Los Angeles



The Stormwater Capture Master Plan (SCMP) considers scenarios that, using aggressive action, could nearly triple the amount of stormwater captured. Source: Rafael Villegas, *Stormwater Capture Master Plan: The Master Planning Process* (Los Angeles: Los Angeles Department of Water and Power, 2014).

Los Angeles will employ additional treatment steps of microfiltration, reverse osmosis, and advanced oxidation to ensure healthy water and to address low levels of contaminants of increasing concern.[17]

The first large-scale, permanent potable water reuse system in the United States was built by the Orange County Water District in 1976 in response to recognition that rapid development of the urban area south of Los Angeles was degrading the quality of the local groundwater basin.[18] Specifically, excessive groundwater extraction had caused seawater intrusion into the coastal aquifer, leading to closure of drinking water wells as far as six kilometers inland.[19] To support the region's ambitious plans for continued growth, the water district adopted a policy of reversing the damage to the coastal aquifer through enhanced freshwater recharge. The main strategy involved the installation of a seawater intrusion barrier (a line of freshwater injection wells) approximately two kilometers from the coast. After ruling out the use of seawater desalination due to its high cost, the utility turned to the local municipal wastewater treatment plant as the source of freshwater for the injection wells.

The initial potable water reuse project, known as Water Factory 21, employed a series of advanced water-treatment technologies (its name refers to its use of twenty-first-century technology). The "factory" consisted of two parallel treatment trains operated side-by-side to purify 0.7 m^3/s (16 million gallons per day) of wastewater effluent. One treatment process train employed activated carbon filtration to remove organic chemicals that might compromise the taste of the water or pose public health risks, while the other train used reverse osmosis to remove contaminants. The reverse osmosis process, which was the more expensive of the two, had the added benefit of reducing the salt content of the water – a necessity due to the fact that the local tap water was rich in salt to begin with, and the modest increase resulting from use and recycling raised the ion content to unpalatable levels.

As the region's need for water increased, the water district tripled the capacity of the system by replacing the original facility with a new treatment plant employing reverse osmosis and an advanced oxidation system against contamination.[20] That facility, the Groundwater Replenishment Facility, has become a standard design replicated by new potable water reuse facilities worldwide, such as the NeWater system in Singapore. Further, the water district's clear communication to the local community of its intentions and commitment to the protection of public health serves as an example of how a water provider can foster legitimacy and public support.[21]

Although the example set by the Orange County Water District established a common design for many potable water recycling systems, the use of reverse osmosis is problematic in inland communities that lack a means of disposing of the salts removed from wastewater effluent. To safely reuse potable water in its inland community, Aurora, Colorado – a rapidly growing suburb of Denver – built a 2.2 m^3/s (50 million gallons per day) facility that subjected water from an effluent-dominated section of the Platte River (where Denver discharged its wastewater effluent) to treatment processes that removed chemical contaminants and waterborne pathogens without producing a salt-brine waste stream.[22] Employing riverbank filtration followed by advanced oxidation and activated carbon filtration, the Prairie Waters Project proved that it was possible to recycle wastewater effluent without reverse osmosis.

Local conditions were key contributors to the design of Aurora's treatment system. The geology of the South Platte River site was favorable to the installation of groundwater extraction wells adjacent to the river (riverbank filtration) and the availability of a drinking-water aquifer made it possible to store the treated water underground. Further, the absence of a convenient means of disposing of salts produced by reverse osmosis created an incentive for the water service provider to purify the water without removing salt. Similarly, local conditions also determine water storage strategies: communities that lack access to a suitable aquifer are forced to store treated water above ground. In addition to posing a greater risk that the public might reject a potable water reuse project due to concerns about the origin of the water (empirical evidence suggests that underground storage plays a role in overcoming concerns about the past history of water),[23] existing surface water storage facilities are usually located at the highest elevations in the city, necessitating significant use of energy to pump recycled water – typically produced at the lowest elevations in the city – to the reservoir.

The issue of salt management and pumping costs were important to the recent decision of a water utility located near Odessa, Texas, to build a potable water reuse facility that recycles approximately 0.11 m^3/s (2.5 million gallons per day) of wastewater effluent. Due to the high concentrations of salt in the local water supply, the Big Spring Water Recycling Facility, like the Orange County Water District's Groundwater Replenishment Facility, employs reverse osmosis and advanced oxidation, though instead of storing the water underground, the facility pipes it directly into a water-supply canal.[24] The decision to recycle the city's wastewater instead of importing freshwater was encouraged by the relatively high cost of pumping water to the city from potential sources, all of which were located at considerably lower elevations than the reservoir.

As illustrated by the examples of potable water reuse in the United States; seawater desalination in Australia; and urban stormwater capture, treatment, and recharge in Los Angeles, new water-supply approaches can provide a viable means of breaking the longstanding dependence of cities on imported water. However, these pioneering efforts were prompted by severe water stress and cities' new willingness to pay for technologies that were expensive relative to conventional options. For cities that are not currently facing acute water stress or that lack the financial means to pay for new technologies, these new approaches may not seem like viable alternatives to existing water-supply approaches. This situation is a common attribute of technology transitions that occur when a new approach replaces an established system.[25] For familiar examples, like wireless communication replacing landlines or data storage moving from floppy discs to cloud-based storage, the time between the first appearance of a new technology and the displacement of an existing technology is shorter than that of a change in civil infrastructure because the replacement cycle is shorter. Nonetheless, transition processes are similar in many respects: initially, new technologies are often more expensive than existing approaches. While they provide benefits relative to existing approaches, the risk of failure in the water sector discourages widespread adoption.[26] After a period of piloting and demonstration-scale projects, water providers with few viable alternatives turn to new technologies and are willing to bear the extra costs and higher risks of failure. After these early adopters have gained experience and thus supported the start-up of a new industry, the costs and risks of failure decrease and a wider cross section of the community can adopt the new approach.

Viewed from the perspective of technology transitions, the pioneering water-supply projects described above are the first stage of the reinvention of urban water systems. After the early adopters have implemented their pioneering projects, the institutional barriers to financing, regulating, and operating these new technologies will diminish and the overall costs of new forms of water supply will become favorable when considered in a triple-bottom-line analysis. We anticipate that in much the same way that urban water systems have undergone periods of rapid change,[27] we will in the coming decades reinvent the way in which we plan, manage, and operate urban water systems.

ENDNOTES

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Dynamic Markets for Dynamic Environments: The Case for Water Marketing

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Abstract: Static models used in economics and ecology ignore dynamic processes at work in both human and natural systems. In the case of water management, whether for quantity or quality, static models fail to connect changing human demands on water systems with changing supplies due to short-run climate variations and long-run climate change. Water markets provide a way of connecting human demands to nature's supplies through prices, which signal values and scarcity. For water markets to make this connection, water rights must be well-defined, enforced, and tradeable. When they are, entrepreneurs are able to meet old and new demands on water ecosystems in novel ways, as examples in this essay illustrate.

Analyzing nature and economies as static systems gravitating toward equilibria distracts our attention from the dynamic forces in both. Focusing, instead, on the dynamic processes at work in the environment and in markets provides a link between the two by emphasizing that 1) environmental problems result from a lack of clear property rights; 2) property rights problems are entrepreneurial opportunities; and 3) entrepreneurs respond to and create market signals, which incorporate environmental conditions.

Economics, in general, and environmental economics, in particular, are saddled with static models. Although economic models of market equilibrium provide useful predictions of tendencies toward equilibrium, they do not tell us much about the process of getting there. Natural resource economic models, meanwhile, emphasize the static notion that private costs are often less than social costs. This allows private actors to ignore some costs of their actions and thereby engage in practices that are not beneficial to society: too much fishing of a stock of fish, too many emissions into the air, and too much diversion of

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water from rivers, for example. The implication, therefore, is that to achieve socially optimal resource use, private action must be curtailed by collective action. This static conclusion fails to recognize that any such divergences result from property rights that are not well-defined and enforced[1] and that property rights are continually evolving.[2]

Just as equilibrium models oversimplify markets and ignore the important dynamic forces of entrepreneurship, environmental models have oversimplified ecological systems and ignored the importance of dynamic organisms. They build on a perspective of natural balance, rather than on ecosystems that are continually confronting and generating new constraints and adjusting to them. In the words of ecologist Daniel Botkin, "We have tended to view nature as a digital camera's [*kodachrome,* as he called it] still life, much like a tourist-guide illustration of La Salute; but nature with and without people is and always has been a moving-picture show, much like the continually changing and complex patterns of the water in the Venetian lagoon."[3] Botkin asks, "How real is the concept of a balance of Nature? What is the connection between people and nature? What are our roles in and obligations to nature?"[4]

As with ecologists, economists must ask: how real are market equilibria? Given that markets are never in equilibrium, we need to focus on dynamic processes in both nature and markets and on the links between human action and nature. Those links are determined by property rights – the rules of the game – that determine who has the right to decide how resources are used and to derive value therefrom. If, at a point in time, property rights are clearly defined and enforced, then the roles and obligations of human beings to one another as users of nature would be clear according to the human values and natural conditions at that time.

As values and environmental conditions change, however, dynamic forces come into play and property rights must evolve: the property rights that had clearly defined roles and responsibilities before the change in conditions may no longer be adequate.[5] Once abundant resources become scarce, individuals with different values will compete for uses, necessitating allocation among competing interests. Effective environmental entrepreneurship, therefore, is akin to Darwinian evolution in economies. It is, as popular science writer Matt Ridley put it, "spontaneously self-ordered through the actions of individuals, rather than ordained by a monarch or a parliament."[6]

Provided property rights are transferable, markets can accommodate changing values and changing environments, but not without entrepreneurs who observe changing values, recognize opportunities, and respond to new demand and supply conditions. The challenge for the entrepreneur is to discover the values of goods, services, and the inputs that go into their production and to capture those values through market exchanges of ownership claims to labor, capital, and natural resources.

When an entrepreneur successfully responds to disequilibrium conditions created by changing human values or by changing ecosystems, he or she is attempting to resolve what Daniel Botkin calls "discordant harmonies."[7] Just as ecological disturbances create discordance in the environment to which species respond by filling niches and evolving, economic disturbances create market discordance to which entrepreneurs respond. If they are successful, they create harmony from dissonance.

Consider more generally how environmental entrepreneurs interface with water resources. With water covering 70 percent of the blue planet's surface, it might appear that water is not scarce enough to attract entrepreneurial attention. Of course, it is scarce because most of it is either in the wrong place or the wrong form. Water is not where the people want to use it; its supply is variable relative to human demands; it is of the wrong quality (whether too saline or too contaminated) to satisfy human demands; or it is unattractive for some combination of these reasons.

This begs the question, why is water different from many other resources? Again, the answer is property rights. Water problems arise when there are competing demands for scarce water, for which property rights are not clear.

The dewatering of rivers in arid parts of the American West offers a classic example.[8] Diversion rights to water in Oregon and California's Klamath River were sufficiently well-defined to allocate the scarce resource among competing uses, even if it meant leaving the river dry. However, because it was so costly to transfer water from diversion to instream uses, it was neither economical nor possible to divert the river to meet the environmental demands for instream flows to support spawning salmon and steelhead, leading to further conflicts about resource allocation. Entrepreneurial responses to competing demands for water use, whether from increased demands or reduced supplies, require reallocating water within the existing institutions or altering those institutions to accommodate new constraints and new allocations.

Water markets offer an increasingly important tool in institutional debates about reallocation and resource use. This paper first explains the importance of markets in providing an interface between dynamic human demands for water resources and dynamic environmental conditions for their supply. It then focuses on examples of the role that entrepreneurs play in dynamic environments and dynamic markets.

Economists have traditionally analyzed markets using comparative statics, comparing one equilibrium with another and specifying the conditions required for the equilibrium to hold. The standard blackboard assumptions of perfect information, costless market transactions, and perfect competition focus attention on points of equilibrium in which the forces of supply and demand are perfectly balanced.

Philosopher Mark Sagoff has confronted economists who view markets and ecosystems as equilibrium systems that can be objectively valued for their contributions to human welfare: "Ecological knowledge, like any kind of empirical knowledge that is relevant to economic activity, is too spread out among people and too sensitive to the moment to be captured by any one individual or by any group – even scientists given sufficient resources." Remarking on recent attempts by economists and scientific experts to assign values to ecosystem services from the top down, Sagoff concluded that the "'ecosystem services' project is bound to fail in its attempt to substitute an *in natura* calculus of value for the artifice of market price."[9] Instead of seeking to valuate ecosystems, markets aggregate disparate knowledge through entrepreneurial action.

Viewing markets as if they exist in equilibrium distracts us from the market processes, entrepreneurial activities, and institutional evolution that tend to move markets in the direction of equilibrium. Just as nature is never in equilibrium, neither are markets. Certainly equilibrium concepts are useful for developing hypotheses and gaining insights into basic market responses to changing conditions, but they obscure the moving picture show of the market process.

Dynamic processes, found in both ecosystems and markets, call for a better understanding of the connection between ecology and economics. In the words of environmental writer Emma Marris, ecosystems are "fundamentally stable entities afflicted by changes from without and within about as much as a ballet is a fundamentally static object afflicted with motion."[10] Marris's description could just as easily apply to markets that, although often viewed as if they exist in balance, are fundamentally driven by a barrage of changes from within and without.

Much like the interaction of organisms in nature, the market process emphasizes the interaction of individuals based on factors that are time- and place-specific. Just as individual species fill niches in ecosystems, entrepreneurs find market niches and specialize in production and marketing to fill those niches. Successful entrepreneurship requires the entrepreneur to use local knowledge and resources more efficiently than is the current practice. As a result, inefficient resource use in markets and in ecosystems is crowded out in an evolutionary process where sustainability requires profitability for survival.

In this sense, human action is ordered spontaneously through market processes just as animal and plant speciation is ordered through evolutionary processes. Information on which niches are opened and how they should be filled cannot be acquired or ordained from the top down; it requires responses to what economist and Nobel laureate Friedrich Hayek described as "rapid adaptation to changes in the particular circumstances of time and place."[11]

The ability of market institutions to resolve conflicting human demands on the environment relies on entrepreneurs who reallocate inputs and outputs guided by market prices and property rights. With clear and transferable property rights, owners of resources will have to compare the value they place on resources with offers made by others. These competing values are embedded in prices, which provide condensed information about individual preference, resource scarcity, and technology, among other inputs.

In her recommendations, Emma Marris has summarized the modern challenges facing environmentalists: "Give up romantic notions of a stable Eden, be honest about goals and costs, keep land from mindless development, and try just about everything."[12] This is what entrepreneurs do. In some cases, their decisions will be wrong. However, just as poor adaptations in nature are eliminated, albeit slowly, via evolutionary processes, bad decisions in markets are purged by economic losses.

In summary, the effectiveness of market processes and entrepreneurship in adapting to changes in nature depends on well-defined, enforced, and transferable property rights to environmental resources. If those rights exist, costs and benefits will be internalized by owners. If they do not, entrepreneurs are incentivized to establish property rights in order to capture the benefits of ownership. The evolution of property rights may come from the bottom up or from political processes that distribute rights.[13] In either case, there is no more guarantee that property rights will be complete than there is that governmental control allocation of environmental assets will respond to dynamic ecosystem changes.

Water markets provide a way of adapting to a dynamic world of changing human demands for water and the changing supplies of it. Doing so via water markets requires that water rights be well-defined, enforced, and transferable. Not surprisingly, water rights vary considerably depending on human demands relative to natural supplies. The Eastern United States relies mainly on the common law of riparian rights, which gives riparian landowners an equal right to an undiminished quantity and quality of water. This system was appropriate given the relative abundance of water in the East and the uses to which water was put: namely, power generation and human consumption, rather than diversion for irrigation.[14] Because prior appropriation rights are more clearly specified, they are more amenable to exchange.[15] This system evolved in response to "institutional entrepreneurs" who found water law from the East inadequate for purposes requiring diversion.[16]

The importance of property rights evolution is seen in the recent allowance of diversion rights to be converted to instream flow rights. The prior appropriation system was based on the "use it or lose it" principle, which required diversion or was considered abandoned, and therefore could be claimed by others. Given the increased value placed on instream flows for water quality, recreation, and environmental amenities, entrepreneurs have brought pressure to change the laws so that every Western state today recognizes instream flows as a beneficial use of water.

Obstructing water entrepreneurs are a variety of political impediments that raise transaction costs for exchange. The battle over water flowing through California's Central Valley into the San Francisco Bay is the quintessential example.[17] The rights to Central Valley water are largely held by agricultural users or are allocated through contracts between agricultural users and the state or federal government. Environmental demands based on the need for water to ensure survival of the delta smelt or migrating salmon have been articulated through political processes, especially the Endangered Species Act. Because it is almost impossible to shift agricultural water to environmental uses through market transactions, the only alternative for environmentalists is politics in which the stakes are high and the battles fierce. Indeed, given the slowness with which bureaucracies move, there is good reason to expect that they may be less dynamic than market entrepreneurs.[18]

Water markets provide an alternative to political allocation that allows flexibility in light of dynamic environmental constraints and human demands. The following are examples of water markets at work and reflect how entrepreneurs respond to disequilibria.

Tradable water rights allow conservation organizations and agriculturalists to negotiate mutually beneficial agreements to share the water. For example, in 2005, Montana Water Trust (now the Clark Fork Coalition) entered into a ten-year lease agreement with irrigators to reduce diversions along Tin Cup Creek in Western Montana. The upper portion of Tin Cup lies within the Selway-Bitterroot Wilderness and provides critical native fish habitat, fostering westslope cutthroat trout and bull trout. The lower portion, however, was heavily appropriated for irrigation use and diversions that depleted stream flows to levels insufficient for fish. With the lease agreements in place and consequent reductions in diversions, instream flow levels were restored, reconnecting migration routes between Upper Tin Cup Creek and the Bitterroot River downstream. In Idaho, the trout and salmon conservation organization Trout Unlimited collaborated with the city of Pocatello to acquire senior water rights upstream from irrigators. The added flows help Trout Unlimited meet its goal of restoring flows for Yellowstone cutthroat trout while the additional water instream improves water quality and reduces the city's need to pump scarce groundwater.[19]

Just as markets are dealing with water scarcity issues, markets can also work to address water quality concerns and the associated economic costs.[20] Though the Clean Water Act does not specifically authorize markets in water quality credits, the act's directive to states to establish plans to control point and nonpoint source pollution ultimately leads to the creation of credit markets.[21] States have been drawn to incentive-based market schemes for controlling pollutant sources because they introduce flexibility in how effluent targets are met, which reduces costs to regulated dischargers while encouraging reductions in pollutant levels. The number of water quality trading programs in the United States has grown considerably since the emergence of the first generation in the 1980s.[22] The Environmental Protection Agency (EPA) identifies forty-eight domestic trading programs in twenty-five states. Such programs are helping states meet water quality standards more efficiently and at reduced costs to regulated industries.

For instance, in the Long Island Sound of New York and Connecticut, runoff and excessive discharges from sewage treatment plants into area streams were threatening local fish and shellfish populations. A coordinated effort between the EPA, the Connecticut Department of Environmental Protection, the New York State Department of Environmental Conservation, and private organizations and landowners developed a watershed-based nutrient reduction plan. Through negotiation among the various interests, the plan established a statewide cap on the total amount of nitrogen that may enter the watershed, and also allocated individual discharge targets to seventy-nine municipal waste treatment plants in the area. If it is too expensive for one plant to meet its target level, it can buy credits from other dischargers that have reduced their pollution levels below their respective targets or permitted levels. Discharge sources with lower control costs have the incentive to reduce pollution amounts, thereby creating tradable pollution credits. Higher-cost dischargers can buy credits and clean up less. Either way, the net amount of discharge does not exceed the total allowed amount.

However, water quality markets still rely on governmental control to establish target levels of pollution. Such a strategy "presumes regulators are correct in their knowledge about how much pollution is 'right.'"[23] But no matter how well-intentioned or informed agency officials may be, it is impossible for them to determine the optimal limit on pollution in every case. Agencies are subject to political pressures and, in promulgating regulations, they set uniform standards that are applied over an overly broad range of pollution contexts. In a true market approach to water quality, the residual claimants determine the acceptable amount of pollution or level of water quality and, through negotiation, the contract for achieving the target level.

Most water quality trading programs are driven by top-down regulations, but some arise through bottom-up collective action. For example, Wichita, Kansas, is paying upstream farmers in the Cheney Lake Watershed to reduce nutrient runoff tied to agricultural production.[24] In the early 1990s, algal blooms and increased sedimentation in Cheney Lake alerted area residents, farmers, and the City of Wichita – which relies on the lake for drinking water – that water quality was no longer something that could be taken for granted. In a region dominated by agricultural users, the source of the pollution was clear, and the offending farmers themselves decided something had to change.

Like many nations, Australia is facing increasingly scarce water resources, a product of supply shocks and increasing competition among consumptive and environmental water demanders.[25] The development of Australian water markets first required institutional changes to provide opportunities for formal markets and a means of balancing water supplies and demands. Early reforms in the 1980s, which created temporary trading opportunities, were followed by broader reforms in 1994, when the Council of Australian Governments (COAG) endorsed the Strategic Framework on Water Reform, laying the foundation for a nationwide transition to formal water markets. Central to the reforms were provisions for defining water entitlements, severing water claims from land, and incorporating environmental flows into water management plans. State and territorial governments were tasked with redefining entitlements in terms of ownership, volume, reliability, transferability, and, if appropriate, quality, while also developing plans to manage water for instream applications.[26] The reforms in the 1990s resulted in "considerable progress toward more efficient and sustainable water management."[27]

If water problems are caused by either the fact that water is not where the people want to use it, that its supply is variable relative to human demands, that it is of the wrong quality to satisfy human demands, or some combination of the three, they will be exacerbated by climate variability. In the context of water, climate change is best thought of in terms of what it means for variations in water supplies and demands. In his book *Windfall: The Booming Business of Global Warming*, McKenzie Funk explains that market responses to climate variation are "tribal, primal, profit-driven, short-term, and not at all idealistic."[28] Seen this way, water markets provide an alternative way of dealing with increased climate variance.

John Dickerson, CEO of Summit Global Management, is harnessing water markets in response to climate variation by investing in what he calls "wet water" – in contrast to water infrastructure – through the purchase of water rights in America's Colorado River basin and in Australia's Murray-Darling basin. As noted above, both sites have reasonably well-defined, enforced, and tradeable water rights to facilitate water marketing. According to Dickerson, "The real future is going to be the direct assets – not through the medium of a utility, not through the medium of a pump company – but the direct, physical water assets."[29] Or as Funk puts it, "Carbon emissions are invisible, temperatures are an abstraction. But melting ice, empty reservoirs, lapping waves, and torrential rainstorms are physical, tangible – the face of climate change. Water is what makes it all real."[30]

Dickerson had trouble raising money for his fund until the publication of Al Gore's *Inconvenient Truth* kick-started the market.[31] Fifteen water mutual funds started in 2007, more than doubling the preexisting number. Funk reports that "[i]n two years, the amount of money under management ballooned tenfold to $13 billion. Credit Suisse, UBS, and Goldman Sachs hired dedicated water analysts."[32]

To help markets along, governments need to follow the lead of Western U.S. states and Australia by making water rights more secure and by encouraging trading. As Dickerson has put it, governments can "allow water to be priced at what it's worth, then create a mechanism by which the rice farmer can sell his water to the wine producer."[33] By buying low and selling high in the American West's Colorado River basin and in Australia's Murray-Darling basin, Dickerson and other speculators are reducing water waste, improving water use efficiency, and hedging against fluctuations in water supply caused by climate variation.

The proposal to create a Colorado River water bank illustrates another way in which markets can adapt to climate variation.[34] In Colorado, agricultural users on the west slope of the Rocky Mountains have more senior water rights than municipal users on the west slope, who divert water eastward across the continental divide. As long as there is sufficient water to meet both senior and junior water rights holders, there is no problem; but when droughts limit supplies, the east-slope municipalities are the first to go dry.

To make matters worse, drought in the upper reaches of the Colorado River is not the only event that drives scarcity: demands from states at the lower end of the river – Nevada, Arizona, and California – who have claims to a share of the river's flow through the Colorado River Compact, can further jeopardize water supplies for east-slope communities. Under that 1922 compact, states in the upper basin (Colorado, New Mexico, Utah, and Wyoming) are required to deliver 7.5 million acre-feet of water per year on a ten-year rolling average to the lower basin states (Arizona, California, and Nevada). If the ten-year rolling average falls below 7.5 million acre-feet, the lower basin states force a "compact curtailment" on the upper basin states. In this case, upper basin junior water rights holders, including many east-slope municipalities, would be the first to be cut off.

Assuming that the marginal value of water to east-slope municipalities is greater than it is to west-slope irrigators, a water bank could significantly improve water use efficiency. The proposed bank would allow west-slope irrigators with senior rights to deposit their rights in a central recording system from which east-slope municipalities with junior rights could purchase a call on the deposited rights. If a compact curtailment occurred, the bank would require lower value irrigation users to meet the call by reducing their diversions, thereby allowing higher-value municipal users to continue their consumption. In a world of greater climate variation, water banking of this sort offers efficiency gains without political battles to determine who gets how much water.

Finally, consider how climate variation can affect conservation efforts: in this case, habitat for migratory shorebirds on their annual journey from South America and Mexico to the Arctic. This journey takes many of the birds through California's Central Valley, where water engineers have harnessed the natural systems to provide water for agricultural, municipal, and industrial uses. In the process, 95 percent of the original wetlands have disappeared.[35]

BirdReturns, an innovative market transaction between bird lovers and farmers, is working to restore wetlands to the region, thereby welcoming birds back. The transaction begins with bird watchers who use a smartphone app called eBird to record shorebird sightings, which are then used by the Cornell University Ornithology Lab in New York to map where water is needed. The Nature Conservancy then uses private donations to pay farmers to flood the fields – which otherwise would have been drained – most directly in the migratory bird flight path. Given that the birds are only there for a short time, the Nature Conservancy does not have to purchase the water outright; it only needs to "rent" it when the birds are in residence. The Nature Conservancy uses a reverse auction in which farmers submit bids and the lowest bidder willing to provide water wins. Through this competition, the Nature Conservancy keeps down the costs of achieving its goal.

The first season of the program ended in April 2014, with birders having reported sightings of all species of birds they hoped to attract to what they have called "pop up" wetlands: ten thousand flooded acres owned by forty farmers. Birders hope to increase the number of shorebirds stopping in California from one hundred seventy thousand to four hundred thousand in both the spring migration north and the fall migration south. Although it is too soon to assess the program's overall success, its potential is summed up by Mark Reynolds, the Nature Conservancy scientist who heads the program: "Migratory birds are a daunting challenge. It's a hemispherical scale, and it's seasonal, and every species has a different life history. This program allows us to be strategic with scarce conservation dollars."[36]

Because the challenge is even more complicated in light of climate variation, innovative contracting of this sort offers great hope for conservation interests.

Dynamic market responses to changing relative prices have always been the best response to the dynamic world in which we live. Typically, we associate market prices as a way of connecting demanders and suppliers of material goods and services, but they are even more important as a mechanism for connecting human demands on our natural world with the dynamic forces of nature. Prices provide condensed information about human demands and, if property rights to inputs are clear and transferable, they provide similar information about the human value of resources in competing uses. When human values for nature's bounty change, entrepreneurs who recognize the change have an incentive to economize by reallocating resources to higher-valued uses. And when the dynamic forces of nature increase or decrease the supply of resources, prices will speak on nature's behalf.

Successful entrepreneurship recognizes when human demands and nature's supply are in discordance, and reallocates resources in ways that harmonize the two. Producing more with fewer resources, discovering new sources, and developing technologies that better use resources are all tools in the entrepreneur's kit.

In order for dynamic markets to respond to dynamic environments, the right institutions – namely, well-defined, enforced, and tradeable property rights – must be in place. Where these institutions exist, as in the American West and Australia, water markets are encouraging development of new supplies, water use efficiency, and technological innovation. Climate variation adds another element to the demand and supply mix to which dynamic markets *may* respond. Whether they *will* respond depends largely on the property rights institutions, which, all too often, are not conducive to market transactions. In such cases, the link between dynamic markets and dynamic ecology is broken. The question then is whether politics can be dynamic enough either to facilitate the creation of new property rights and reduce transaction costs or to respond to dynamic ecology. There are some bright signs in the emergence of water markets, but, as Mark Twain supposedly put it, "Whiskey is for drinkin' and water is for fightin,'" and legislatures and courts are often the barroom in which the fightin' occurs.

ENDNOTES

[1] See Ronald H. Coase, "The Problem of Social Cost," *Journal of Law and Economics* 3 (October 1960): 1 – 44.

[2] See Harold Demsetz, "Toward a Theory of Property Rights," *American Economic Review: Papers and Proceedings* 57 (2): 347 – 359; and Terry L. Anderson and Peter J. Hill, "The Evolution of Property Rights: A Study of the American West," *Journal of Law and Economics* 18 (1): 163 – 179.

[3] Daniel B. Botkin, *The Moon in the Nautilus Shell: Discordant Harmonies Revisited* (Oxford: Oxford University Press, 2012), 3.

[4] Ibid., 18.

[5] This analysis may seem unduly anthropocentric because it presumes that property rights are held by humans over nature. Some legal scholars have argued that flora, fauna, and even inanimate objects have rights, but accepting this, those rights can only be expressed by humans making claims for things in nature. All rights that have any meaning in our world therefore boil down to human rights, even if those rights are expressing an intrinsic value of nature.

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[8] See Charles J. Vörösmarty, Michel Meybeck, and Christopher L. Pastore, "Impair-then-Repair: A Brief History & Global-Scale Hypothesis Regarding Human-Water Interactions in the Anthropocene," *Dædalus* 144 (3) (2015): 94–109.

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[11] Friedrich A. Hayek, "The Use of Knowledge in Society," *American Economic Review* 35 (4): 519–530.

[12] Marris, *Rambunctious Garden*, 170.

[13] See Terry L. Anderson and Peter J. Hill, *The Not So Wild, Wild West: Property Rights on the Frontier* (Stanford, Calif.: Stanford University Press, 2004).

[14] Increasing urban demands that require water diversion and delivery to cities not located on streams have challenged the riparian system. See Terry L. Anderson, Brandon Scarborough, and Lawrence R. Watson, *Tapping Water Markets* (New York: RFF/Routledge, 2012), ch. 6.

[15] The priority system could also be based on an equal sharing or on a collective determination of the importance of various uses when supplies are not sufficient to meet all demands. The important element of water rights for market transactions is that they be clearly defined, enforced, and transferable.

[16] For further discussion of institutional entrepreneurship, see Anderson and Hill, *The Not So Wild, Wild West*, ch. 2.

[17] See Katharine L. Jacobs and Lester Snow, "Adaptation in the Water Sector: Science & Institutions," *Dædalus* 144 (3) (2015): 59–71.

[18] For a good discussion of political and bureaucratic processes, see Randy T. Simmons, *Beyond Politics: The Roots of Government Failure* (Oakland, Calif.: Independent Institute, 2011).

[19] Trout Unlimited, "Western Water Projects," http://www.tu.org/tu-programs/western-water. See also Clark Fork Coalition, "Bitterroot," http://clarkfork.org/our-work/where-we-work/bitterroot/.

[20] See Adena R. Rissman and Stephen R. Carpenter, "Progress on Nonpoint Pollution: Barriers & Opportunities," *Dædalus* 144 (3) (2015): 35–47.

[21] Esther Bartfeld, "Point-Nonpoint Source Trading: Looking Beyond Potential Cost Savings," *Environmental Law* 23 (1993): 43–106.

[22] In a worldwide survey, the World Resources Institute identified six trading programs outside the United States: four active programs (three in Australia and one in New Zealand) and two in development (one in Australia and one in New Zealand). See Mindy Selman, Suzie Greenhalgh, Evan Branosky, Cy Jones, and Jenny Guiling, "Water Quality Trading Programs: An International Overview," *WRI Issue Brief*, No.1 (March 2009).

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Impair-then-Repair: A Brief History & Global-Scale Hypothesis Regarding Human-Water Interactions in the Anthropocene

Charles J. Vörösmarty, Michel Meybeck
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Abstract: Water is an essential building block of the Earth system and a nonsubstitutable resource upon which humankind must depend. But a growing body of evidence shows that freshwater faces a pandemic array of challenges. Today we can observe a globally significant but collectively unorganized approach to addressing them. Under modern water management schemes, impairment accumulates with increasing wealth but is then remedied by costly, after-the-fact technological investments. This strategy of treating symptoms rather than underlying causes is practiced widely across rich countries but leaves poor nations and many of the world's freshwater life-forms at risk. The seeds of this modern "impair-then-repair" mentality for water management were planted long ago, yet the wisdom of our "water traditions" may be ill-suited to an increasingly crowded planet. Focusing on rivers, which collectively satisfy the bulk of the world's freshwater needs, this essay explores the past, present, and possible future of human-water interactions. We conclude by presenting the impair-then-repair paradigm as a testable, global-scale hypothesis with the aim of stimulating not only systematic study of the impairment process but also the search for innovative solutions. Such an endeavor must unite and cobalance perspectives from the natural sciences and the humanities.

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Greenhouse warming and potential changes to the hydrologic cycle figure prominently in the climate-change debate, but many other direct anthropogenic factors are today redefining the state of rivers, which supply around 80 percent of renewable freshwater to society.[1] Chief among these are widespread land-use change, urbanization, industrialization, and pollution, all known to stress aquatic ecosystems. The highly positive impacts of a reliable water supply on economic productivity (which requires waterworks like dams, irrigation, and interbasin transfers), means that the water cycle will increasingly be controlled by humans for decades if not centuries to

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come, a hallmark of the new geological epoch called the Anthropocene.[2] With human control of water also comes the specter of water conflict, an issue emphasized by several high-profile research studies, including the last rounds of the Intergovernmental Panel on Climate Change (IPCC), the U.S. National Climate Assessment, and the National Intelligence Estimate.

Water crises are not restricted to humans alone. Freshwater ecosystems are critical biodiversity hotspots. Occupying less than 1 percent of the Earth's surface, they provide habitat to more than 125,000 cataloged species and one-third of all vertebrates and affiliated taxa.[3] Their restricted spatial extent belies their importance, as they maintain orders of magnitude more species per unit area than their terrestrial or oceanic counterparts. The intimate connection and importance of rivers, lakes, and wetlands to human society, coupled with mismanagement, pollution, and climate change, produces the highest potential loss of species on the planet. By some estimates, between ten and twenty thousand species have been lost to date.[4]

Their current stress notwithstanding, water systems will be relied upon over the next several decades to deliver reliable services in light of anticipated economic development and population growth.[5] We refer here to ecosystem services, the array of public goods and functions that nature conveys and which will in the long term sustain human society. These include provisioning benefits like clean drinking water, navigation, waste dilution, transportation, food, and energy production. Ecosystem services also include important regulatory functions (such as climate control) and supporting functions of the biosphere (such as the cycling of essential nutrients). While the value of all these services is subject to debate, they likely make possible a sizable but poorly quantified fraction of global GDP.[6] Despite their clear importance, a survey of the world's major biomes at the turn of the century shows that in virtually all cases "natural capital" is being actively lost, degraded, or co-opted by humans.[7] It remains an open question how available and capable such services will be to serve the water needs of society over the long haul.[8] The answer concerns an issue no less important than how we humans place the planet's sustainability – and our own water security – in the balance. For freshwater, the preliminary outlook is sobering.

An initial global analysis of risks to river systems presented in 2010 confirmed previous reports that threats to human water security and biodiversity are widespread and pervasive.[9] Nearly five billion people live in close proximity to or directly rely on water systems whose ambient condition is moderately to severely impaired. The study also exposed a previously unrecognized global water management principle under which high levels of incident threat to human water security are allowed to accumulate but are then mitigated through an annual global investment of $0.5 trillion in water technologies and engineering.[10] Because such investments are today directed overwhelmingly toward rich or rapidly emerging economies, this impair-then-repair strategy strands the world's poor in a precarious state. Nonetheless, water security also preoccupies the highly developed countries, as John Briscoe's essay in this issue details.[11]

The impair-then-repair approach also distorts public perception of water challenges and contributes to our collective tolerance of the status quo and resistance to change, which is endemic even in rich countries with the technical wherewithal and mature environmental regulations to institute otherwise sensible conservation measures (see also Jerald Schnoor's essay in this volume).[12] In rich countries, an expensive technological curtain separates us from a generally impaired ambient water environment and the clean, reliable water supplies we draw from the tap. A series of surveys published in 2008 and 2010 shows that two-thirds of the American public believes the nation is stable or making progress on environmental pollution whereas two-thirds of the Chinese public believes that water pollution is a "moderately big" or "very big" problem.[13] The mapping study showed very similar levels of threat to water resources in the United States and China, directly at odds with the U.S. public's perception.[14]

The state of water and water management today did not materialize spontaneously. It is more accurate to consider the contemporary setting as but an instant in historical time, conditioned on decades if not centuries of past human behavior (and, as Michael Witzel argues in this volume, belief systems).[15] How, why, and when did such a globally pervasive management strategy emerge? And where is it likely to take us in the future? Using examples from the historical literature, we address this subject in the next sections.

While our interactions with natural and engineered water systems have been part and parcel of human history since the dawn of civilization, the more recent evolution of human-water systems in the Northeastern United States is instructive, as the region moved from a nearly pristine state under indigenous management to today's post-industrial condition in only a few hundred years.[16] The impair-and-repair pattern is clearly evident in seventeenth- and eighteenth-century urban development. Soon after arriving in Boston in 1630, settlers began tapping groundwaters; by 1678 there were so many wells that city streets periodically flooded.[17] In New York, where seawater and sewage periodically fouled wells, the Common Council issued municipal bonds to construct a steam-powered waterworks, holding pond, and network of wooden pipes in 1774, only to have the project derailed by the Revolutionary War.[18] By the mid-1700s, Philadelphia also had a system of public wells. Responding to a yellow fever outbreak believed to be linked to tainted water, Philadelphians began piping water into the city by 1801, creating one of the largest and most advanced urban water systems in the world at the time.[19]

With continued urbanization in the nineteenth century, municipalities faced growing pollution problems. In 1833, Boston announced plans to pipe water into the city because the local supply had become "highly impregnated with the deleterious contents of cesspools and drains."[20] In response, a greatly expanded municipal water system transferred water from Cochituate Lake nearly twenty miles into Boston "to provide for the health, security, cleanliness and comfort of the city."[21] Similarly, Baltimore, Philadelphia, and New York enacted measures to protect water supplies from contamination. With breakthroughs in the germ theory of disease in the 1880s, bacteriologists identified the pathogens responsible for cholera and typhoid. In response, sanitation engineers began experimenting with sand filters, which twenty cities had installed by 1900. By 1910 cities began disinfecting their water with chlorine as a remediation measure.[22]

The ease with which water could be drawn from the tap led Boston authorities to criticize the citizenry's increasingly wasteful ways. Appalled that Bostonians were using nearly one hundred gallons per person per day (compared to the three to five gallons typically drawn from pumped wells), the local water board exclaimed in 1860 that the city consumed water at "an amount believed to be without parallel in the civilized world."[23] In response, Boston annexed several neighboring communities and extended pipes and aqueducts through them to secure new water supplies.[24] Similarly, New York expanded its waterworks, constructing a reservoir in Central Park in 1862 and building a new larger Croton Aqueduct and Dam, which at 1,600 feet long and 240 feet high was the largest masonry dam in the world upon its completion in 1906.[25] By the beginning of the twentieth century, there were more than 3,100 waterworks piping water into urban households across the United States. Heavily engineered water systems had become the norm.[26]

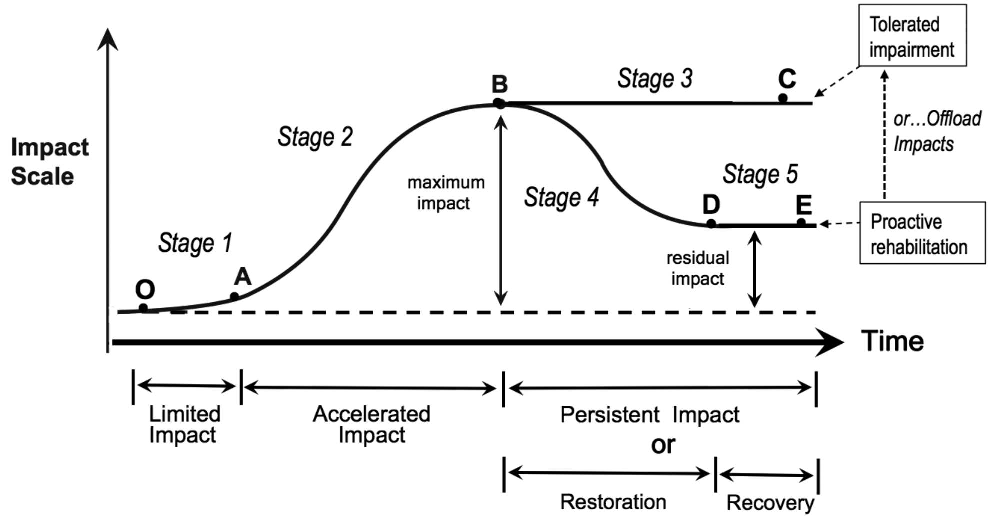
Industrialization further reshaped the ways humans interacted with their water systems. Increasingly, a river's value lay in its capacity to be modified for human use.[27] Human dominance of water, even if later revealed to be impairing water systems, became a potent symbol of progress. It was far better to use, abuse, and later mend (or ignore) a river than to neglect its development potential. Thus, early solutions lay in new water infrastructure and technology, a fortuitous development as the region ran out of undeveloped land and the pristine water associated with it. A time-honored tradition of fouling and then fixing waterways became an economic necessity.

By their very nature, rivers are important conduits for materials recruited from upland watersheds, transported downstream, and processed through river corridors leading to the sea. By their very nature, humans both accelerate and decelerate this transport of material. One example is the widespread increase of field erosion due to poor land management paired with widespread reservoir construction that intercepts and settles riverborne sediment in the quiet holding waters behind engineered dams. Globally, reservoirs have ultimately won out, with one estimate indicating that only two-thirds of all continental sediment destined for the world's oceans makes it there,[28] placing at risk coastal systems that depend on riverborne sediment to prevent coastal erosion. This includes river deltas, a coastal landform inhabited by a half-billion people.[29] Clearly, what happens upstream does not stay upstream.

These hydrologically mediated "teleconnections" are augmented by economically driven ones whose impacts extend well beyond any local drainage basin. In early stages of development, human impact on water systems is limited to the river basin where the water is actually used. But with urban growth and industrialization, impacts easily spill over into the hinterlands that sustain human populations living in the city.[30] In Paris during the early 1800s, food supply systems serving the city were limited to the Seine basin.[31] But a century later, animal products traveled an average of about 300 kilometers to market. These distances have continued to increase; the travel distance for meat and milk has doubled, while the distance for fruit increased eight-fold. Today, Paris, a megacity of ten million, obtains its grain, meat, and vegetables from an enormous swath of real estate extending from the Seine and other French watersheds to Brazil and Argentina.

Such teleconnections thus affect rivers thousands of kilometers from the centers of demand. While Parisians enjoy world-class cuisine, rivers draining croplands in South America bear the brunt of the pollution and other impacts associated with industrial agriculture. The damming of the James Bay rivers in Northern Quebec to supply New England cities with electricity has resulted in a major impact on regional water resources, the environment, and society far from the point of consumption.[32] Cotton and wheat production in the Aral Sea basin, begun in the 1950s by the Soviets and still expanding, places Central Asian countries today at the forefront of water consumption on a per capita basis world-

Figure 1
A Heuristic Model or Typology of Water System Impacts and Societal Response to Water-Related Environmental Stress



This typology represents a time series of development for a particular region or country (such as for Europe or the United States historically, or a developing region currently or in the future). It can also depict the status of regions or countries at different levels of economic development (poor countries to the left, rich to the right). In addition to investments in environmental protection, local-scale impacts can be reduced by employing the global economy to outsource threat-producing activities. Source: Image prepared by authors.

wide.[33] The cotton worn throughout the world demonstrates how the water demands of a globalized consumer economy can yield one of the world's most catastrophic environmental disasters: the death of the Aral Sea.

As with the many other impair-then-repair examples, these far-reaching impacts are nothing new. Silver extraction by the Spanish in Peru over the course of five hundred years has required the continuous import and then release of enormous quantities of mercury (100,000 tons in total from two European mines in Slovenia and Spain).[34] The impacts of mercury extraction in all three countries over the *longue durée* illustrate the capacity of globalization to reconfigure the geography of water-resource systems.

Based on these many documented narratives, we present here a multistage typology of river development as a time series of human-water interactions in a particular river basin or region. Alternatively, the typology can be regarded as a contemporary snapshot of rivers distributed along a global gradient of impairment. Examples from Europe and the United States are emphasized, given their well-documented histories across each of the stages.

Stage 1 (O – A; Figure 1) rivers are basically intact but also show the early impact of humans. Rivers provide basic goods (such as food) and services (such as floodplain agriculture, river transport), and societies adapt well to their dynamics (as had the ancient Egyptians, whose culture, sustenance, and economies were wellmatched to the rise and fall of the Nile's annual floods).[35] Both water use and pollution from physiological wastes (organic carbon and nutrients in human and livestock excrement) are more or less directly proportional to population. Deterioration of water quality is mainly from bacterial pathogens and lowered dissolved oxygen, conditions arising from the release of domestic and agricultural waste that overwhelms the dilution and self-purification capacity of receiving waters.

In traditional or early development cultures, Stage 1 impacts accumulate gradually over decades or centuries to reveal the fingerprint of human activity. A good example is the physical disruption of small-stream diversions for fish and mill ponds in Europe starting in the early Middle Ages. The mills ultimately proliferated to the point that peasants had rarely to travel more than 5 kilometers to process their products.[36] Records of sedimentation in European lake cores also show medieval deforestation increasing natural soil erosion and sediment transfers by factors of ten to one hundred.[37] Early mining and metal use in Western Europe produced the earliest evidence of environmental pollution as recorded in sediments and peat deposits. In Spain's Rio Tinto, the first Early Bronze Age gold mines (c. 2500 BC) increased lead, mercury, and gold levels on river particles by one-hundredfold over natural background levels.[38]

Some Stage 1 systems can completely modify land and waterscapes for human benefit without necessarily impairing their function. This is true for traditional Asian rice cultivation and was the case for the irrigation systems of Egypt until the mid-twentieth century. In Stage 1, major engineering works are absent or very limited and there is no real impact on aquatic life forms or fish diversity. Nevertheless, these early technical innovations could be truly impressive and greatly outlast the societies that commissioned them, as with the Cloaca Maxima, a stone-lined canal constructed c. 600 BC that served as the main sewer in Rome until the twentieth century.[39]

Before 1800, Stage 1 could easily be found on all continents, even in heavily populated Europe where high levels of impact were mainly concentrated downstream of major cities.[40] Today, Stage 1 can be found wherever large river systems are outside the reach of significant numbers of humans and thus nearly pristine (for example, in Amazonia, Eastern Siberia, Alaska, Northern Canada, New Guinea, and Patagonia). Yet the byproducts of modern society extend to the far corners of the Earth (via transboundary air pollution, for instance), and virtually no location is without evidence of the Anthropocene.[41]

Stage 2 (A – B; Figure 1) shows accelerated environmental degradation, typically linked to urbanization, with pollution increasing faster than population.[42] It arises when traditional recycling systems are abandoned in favor of those that use and release large quantities of imported materials, as when manufactured fertilizers replace domestic wastes in agriculture that then leach into rivers.[43] In Western Europe, urban waste collection began in the mid-1800s after the London epidemics and was generally available after 1875 in some big cities (Paris, Berlin).[44] Best practices for sewage treatment then were rudimentary and emphasized land disposal of wastes collected from cities. In the suburbs, individual waste disposal was the general rule, leading to frequent leaks and major degradation of groundwaters (those within and around Paris were still loaded with excessive nitrates in 1900). Land disposal lasted nearly one hundred years for Berlin. During this period, sewage connections expanded at faster rates than did treatment capacities, thus creating "sacrificed" rivers whose natural dilution and assimilation capacities were overwhelmed.[45]

Impacts of Stage 2 management strategies were largely unknown before the 1950s and, even if demonstrated (such as when oxygen deficits were discovered in the Ohio River in the 1920s), they were accepted as a necessary price to pay for development. After World War II, proliferation of wastewater treatment plants gradually outpaced the rise in sewage collection, which yielded some improvement. Maximum degradation (B; Figure 1) was reached soon after World War II and associated with the loss of most fish downstream of Brussels, Milan, and Paris, with only a few resistant and invasive species surviving.[46] Health impacts were generally left unaddressed, as were ecological consequences.

The end of Stage 2 (B; Figure 1) represents a "moment of truth" for environmental stewardship and a turning point between tolerating persistent impairment and commencing rehabilitation. Even with active investment in remediation, a plateau can persist (B – C; Figure 1), reflecting the collective inertia of impaired biological and physical processes.[47] Depending on the particular issue at hand, Stage 3 may last for decades, as was the case for the organic pollution and fecal contamination across Europe – most clearly exemplified by the Seine downstream of Paris (which was contaminated from 1880 to 1990) or the Zenne River in Brussels (which was totally devoid of oxygen from 1900 to 2005).[48] Chloride pollution in the Rhine persists, with France now facing a severe salinity problem on its major Alsace aquifer that could last for more than three hundred years in some places.[49] In the United States, remediation of toxic and even radioactive chemical pollution is addressed at several Superfund sites,[50] yet legacies can affect densely settled areas and aquatic environments for decades or more.[51] Impair-then-repair is a long and costly process.

The alternative represented by Stage 4 (B – D; Figure 1) sees the fruits of a proactive response to environmental degradation even in light of continued economic growth. Environmental laws are assertively formulated and enforced. A gradual improvement in water quality takes place, typically beginning with reductions in organic and bacterial pollution that increase oxygen levels, then control of eutrophication, acidification, metal contamination, and organic micropollutants. Sewage and industrial treatment outpaces the mere collection and transport of waste streams, and per-capita water use and consumption of pollution-generating products begin to stabilize and decline.

Stage 4 rehabilitation can be rapid in light of aggressive regulation. Signs of environmental recovery emerged not long after the ban of DDT and PCBs, two organochlorinated products synthesized before World War II and largely used in the United States and Western Europe from 1945 to 1970. Sediment cores taken from the Mississippi Delta in the mid-1980s revealed a sharp decline in these chemicals and in lead particulate – a clear indication of how political willpower, financial investment, and technology can be combined to create environmental benefits.[52]

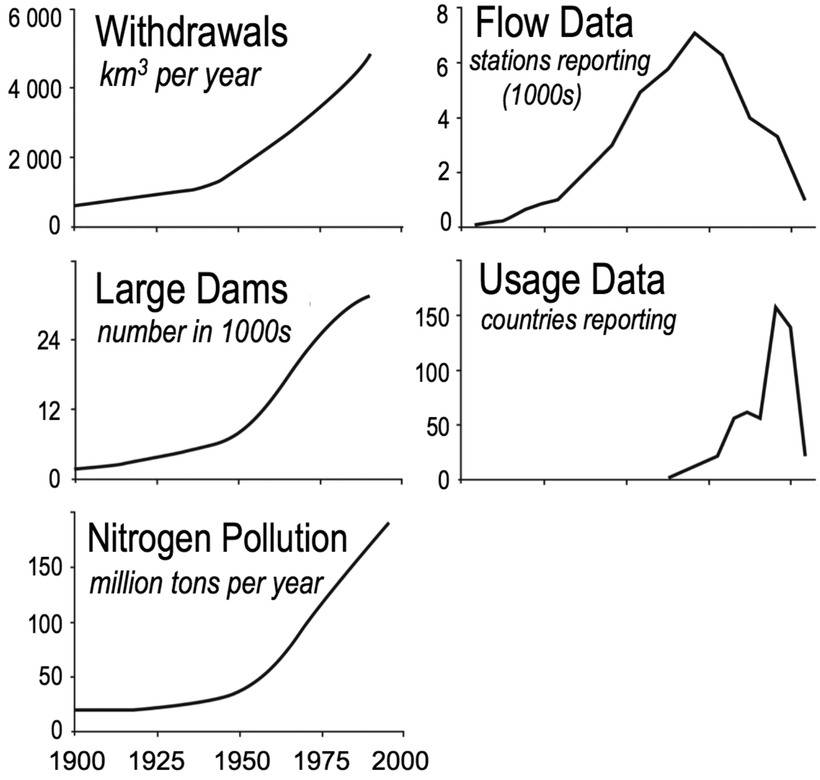
Rehabilitation in Stage 4 also reflects the broad currents of economic development and technology. In the Seine, for example, metal contamination began to ease in the 1960s, a full two decades before any EU regulations. This can be attributed to industrial efficiency gains such as metal recycling in plating industries and to the economically motivated relocation of most pollution-producing industries outside of Paris in the 1950s, then outside of the Seine basin in the 1970s, and finally outside the country.[53] Environmental improvements are also linked to major political change. After the collapse of the Berlin Wall, water quality in the Elbe River improved markedly due to the closure of many industries.[54] More broadly, global redistribution of manufacturing processes – many generating dangerous byproducts like toxins and heavy metals – represents an opportunity to offload environmental threats from the developed countries to rapidly developing parts of the world like China and India.

Stage 5 (D – E; Figure 1) represents rehabilitation and sustained recovery when river waters are managed to maintain the previously won gains in environmental integrity. River systems are purposefully engineered to sustain an array of benefits to society and aquatic biota alike, recognizing the legitimate needs of both humans and nature for water and promoting well-designed co-use strategies. Even among the success stories, rehabilitation can last one to two generations and bear extreme costs. In the Yamato-gawa River draining Osaka, Japan it took forty years and $80 billion to rehabilitate this relatively modest basin (one hundred times smaller than the Mississippi).[55] It took twenty-five years to overcome the organic pollution problem in the Rhine with a total expenditure of $65 billion, or $50 per capita per year.[56] Legacy effects, including loss of habitat, biodiversity, and the integrity of surrounding landscapes, mean that the system may never return to its predevelopment state.[57] Singapore is a rare example of a development trajectory moving directly from Stage 1 to Stage 5 without major impairment. Another example is Switzerland, which addressed eutrophication of its water bodies in 1985 through early detergent bans. Swiss rivers display the benefits of taking a proactive stance, as they never reached the level of degradation observed in other European rivers.

Some rehabilitation strategies are both conceptually simple and cost-effective. In the Danube River Project between Vienna and Bratislava, restoration focuses on reconnecting the riparian forest to the river.[58] The aim is to re-establish hydraulic links between the river, groundwaters, and lowland forests that constitute critical habitat and nursery grounds for aquatic life as well as natural flood and water quality protection. For a relatively modest "reconnection fee" of approximately $100 million annually, this large and economically essential river can still be navigated by huge barges and boats crossing Europe from the Black to the North Sea and yet limit the negative environmental impacts historically linked to human use.[59] These reestablished hydraulic links and "green infrastructure" strategies are now recognized as standard procedure by a new generation of environmental engineers, who often train at the same schools that earlier created "hard-path" engineering in the form of massive dams, locks, and river channelization schemes throughout the twentieth century.

What might the future hold? Worldwide, it is safe to say that rivers have evolved much faster in the past fifty years than in the previous five thousand due to the rapid rise in human use and abuse of this strategic resource. The countless human decisions made each day about water that are executed at the local (and indeed at the individual business or household) level should not obscure the fact that their cumulative impact gives rise to a global-scale syndrome.[60] Figure 2 shows a century-scale trajectory of some key variables, each with well-known and negative impacts on rivers.[61] Humans have stumbled into many of the same pitfalls throughout history, and we see little reason to expect that the social, technological, and economic inertia represented by these curves will be reversed quickly or easily. The figure also shows that our willingness or capacity to monitor the changing state of affairs is completely out of step with the realities of intensifying water stress and concerns about water as the "oil of the twenty-first century." Thus we see a long future for impair-then-repair stewardship.

Figure 2
Human Use and Pressures on Freshwater Resources and Ecosystems



Century-scale inertia on climate progress can be seen in the graphs on the left. At the same time, available monitoring data at UN-designated repositories (right) are in severe decline due to funding cutbacks, commercialization, intellectual property rights restrictions, and delays in data analysis. Source: Data from David L. Strayer and David Dudgeon, "Freshwater Biodiversity Conservation: Recent Progress and Future Challenges," *Journal of the North American Benthological Society* 29 (2010): 344–358, doi:10.1899/08-171.1; Global Runoff Data Centre (GRDC), *Global Runoff Data Base – Statistics* 2012, http://www.bafg.de/GRDC/EN/01_grdc/13_dtbse/db_stat.html?nn=762018; and Food and Agriculture Organization of the United Nations (FAO), Aquastat, http://www.fao.org/nr/water/aquastat/main/index.stm.

Some of the impetus for this management approach is undoubtedly rooted in the economic incentives perceived by an industrial water sector slated to gross more than $1 trillion in annual revenues over the next ten years.[62] In the case of a much-cited water-sector blueprint for the future, there is no single mention of the word *biodiversity* and only one formal use of the phrase *ecosystem services*; other high-profile syntheses advance similarly anthropocentric perspectives.[63] We see this human-nature dichotomy as artificial and as a limit to our ability to meaningfully define future risks to freshwater. Not surprisingly, some of the very threats to aquatic biodiversity – combined effects of poor land management, overuse of water, or even our inability to accurately assess nonpoint pollution[64] – pose a high risk to human water systems. But threats to one do not universally mean threats to the other, as is the case with dams and reservoirs, which negatively impact aquatic biodiversity by disrupting essential flow and temperature regimes and blocking fish migration, yet provide important benefits to society in terms of water supply and flood control. Artificial reservoirs have a pandemic and negative impact on aquatic ecosystems, but their benefits to human water security now total in the trillions of USD. This contrast sets the stage for a major decision point for humankind as it contemplates the nature of sustainable development.[65]

As a result of the unending quest for reliable water supplies – whether pursued though engineered solutions or more haphazardly in the course of development – we run the risk of systematically destroying the free natural subsidies conveyed by well-functioning ecosystems.[66] Losses can be irretrievable, like extinct species, or costly to replace, like natural floodplains that are destroyed and then replaced by massive flood-control infrastructure. This need not be the case, as ecological engineering and "green" alternatives, which emphasize preservation and prevention, are maturing.[67] Yet only $10 billion is spent annually on all protected landscapes and watersheds: a mere 2 percent of current water-sector income.[68]

The necessary socioeconomic and policy conditions for river restoration have taken more than a century to coalesce across the West during a time when scientific and technical know-how was still very limited. We understand far more today about how rivers function and how they can be protected. So in some sense, there is no excuse for inaction. While we can cite individual success stories, we see little evidence of a broad-scale adoption of integrated water resource management, the commonly accepted gold standard for environmental protection of water resources.[69] It will take time, money, water-literacy, and proactive problem avoidance to effect meaningful change.[70] Clear lines of communication between scientists and policy-makers are also essential (see Katharine Jacobs and Lester Snow's essay in this volume).[71]

The world's rapidly emerging economies provide a unique opportunity space for instituting more sustainable, cost-effective, and prevention-oriented approaches to water development, but new market dynamics and incentives harmonized with natural variability in the hydrologic cycle will be necessary (see Terry Anderson in this volume). Developing economies need not repeat the costly mistakes made by rich countries in the past and be relegated to a perpetual reliance on capital- and debt-intensive solutions. Exporting the developed world's impair-then-repair model thus has serious implications for human rights and environmental justice – especially among the poor, who are increasingly impacted by fundamental changes to the world's hydrosystems. Given the emergence of a global middle class in the next two decades, the window of opportunity for meaningful change will be short.[72] The need for innovative solutions, particularly when densely populated regions face absolute scarcity, has never been clearer.

We do not take issue with the countless well-recognized benefits that water infrastructure and engineering systems convey to society, but at some point the world must ask itself: *At what price?* And: *Are there workable alternatives to the current approaches?* Our collective capacity to design sustainable solutions for the future (like those proposed by Richard Luthy and David Sedlak in this issue) that protect valuable water resources in the context of growing environmental and climate stress, dwindling energy resources, and (quite likely) shrinking investment capital, remains an open question. Indeed, when it comes to breaking with the deep historical roots that bind us to the status quo, we face more a crisis of confidence or willpower than a lack of sensible ecosystem-based alternatives or the scientific and technical means to bring them to fruition.

In conclusion, we issue a call-to-research: to systematically test our hypothesis that the impair-then-repair model has guided human-water interactions throughout the Anthropocene and has in the process accumulated globally significant century-scale impacts. This challenge requires a fundamentally new type of collaboration, which must simultaneously explore the biogeophysical, social, and economic forces that shape an increasingly human-dominated global hydrologic system. It will require dissolving the distinctions between the natural sciences and the humanities and between the traditions of scholarship that emphasize quantitative information and those that emphasize narrative approaches. We see equal value in assessing information derived from numerical models and engineering analyses as from indigenous knowledge, cultural anthropology, and historical records. If our hypothesis holds, it will represent an important step toward raising awareness that the impacts of water management easily reverberate far beyond the local domain and ultimately generate global-scale impacts and multigenerational legacies. We see such self-awareness as a necessary precursor to reversing the many deeply entrenched habits that continue to undermine an essential strategic resource.

ENDNOTES

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