Water, Climate, Energy, Food: Inseparable & Indispensable

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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.

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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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