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## Water Sustainability in a Changing World

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### Introduction

What is “water sustainability” and why is it so important? Definitions usually involve a long-term view towards water sufficiency. Water sustainability could be defined as supplying or being supplied with water for life or, perhaps more precisely, as *the continual supply of clean water for human uses and for other living things*. It does not specify exactly how much water we have, nor does it imply the unrestrained, infinite availability of water. Rather, it refers to the sufficient availability of water into the foreseeable future.

Water is, after all, a renewable resource, so sustaining its uses should be possible, shouldn't it? But it turns out that we can have too much water or too little water to meet our needs. Water availability is constrained by natural processes, water allocations across jurisdictional boundaries, the infrastructure necessary to

deliver water for use, and human impacts on water quality and quantity. Various forces affect the nature, timing, and availability of water, which change throughout time. We shall call these forces the “drivers” at play in the world today.

### The Drivers

Water, like all things on planet Earth, is changing. For the most part, these changes are driven by *human activities*, not nature. Water is changing due to our population growth and migration; it is changing from land use pressures and our energy choices; and it is changing due to a shifting climate (Schnoor, 2008). Water scarcity afflicts poor people most seriously, and global development goals are crucial for attaining a semblance of water sustainability for the impoverished.

The following four drivers have caused precipitous changes in water quantity, availability, and quality:

- Population growth.
- Climate change.
- Land use change and energy choices.
- Global poverty.

Our environment has been dramatically altered during the past few decades. Effects are visited at the local, regional, and global scales.

At the local scale, the four drivers cause profound problems for human families in gaining access to quality water. 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 water must evolve to meet this challenge.

**Population Growth.** Population has been growing since the dawn of civilization. Mankind required thousands of years to reach a population of 1-billion people in 1800 A.D. But we only required 125 more years to reach 2 billion, 33 years more years to reach 3 billion, and about 13 to 14 more years for each additional billion people. Population has increased monotonically (continuously), except for a brief history in time when the bubonic plague decimated the world from 1200 to 1300 A.D. It has been estimated that humans already use approximately 54 percent of all freshwater available (Postel et al., 1996), so the future is highly constrained considering the global trend towards increasing population and migration to coastal megacities, many of which are already located in semi-arid regions and are water short.

More water is required to satisfy the needs of a growing population. Individuals only require about 2 liters of water per day for drinking, but the United Nations Environment Program estimates that all activities of society require a minimum of 1,700 cubic meters per capita per year ( $\text{m}^3/\text{capita}\text{-yr}$ ) to live freely from water stress (Water Resources Institute, 2000). Many countries, including India, Germany, Saudi Arabia, and all of northern Africa, already have far less water than that available in groundwater and surface water sources. Egypt survives on less than  $26 \text{ m}^3/\text{capita}\text{-yr}$  of water, partly by importing “embedded” or “virtual” water obtained from products like fruit and vegetables, which demand large quantities of

water where they are grown. To make matters worse, the United Nations Environment Program estimates that the average per capita supply of water will decline by one-third by 2025. Severe scarcity is projected for a majority of the world’s population by 2050 during dry periods in more than 60 countries.

Populations are migrating to coastal megacities (populations greater than 10 million), where providing freshwater for all is difficult. More than 50 percent of humans live in coastal cities already, and likewise 54 percent of the population in the United States now resides in coastal counties. Demographers believe the trend will continue. Desalination of seawater is not an option for most poor and developed countries because the cost is too high.

Globally, where population densities are low, the threat of severe water shortage is lessened. But where population densities are high, any decline in water availability or increase in population may be disastrous. It is often said that we do not have problems with the amount of precipitation, but rather with its distribution. This distinction may be of little consequence because it is not generally possible to redistribute water from water-rich areas to water-short areas, at least not in poor and developing countries.

Southern California conveys snowmelt water from the Sierra Nevada (and a portion of the Colorado River) to provide water supply for 20-million people today. But the precipitation falling on Southern California itself is only sufficient for about 1-million people over the long term. Clearly, the dense population of the coastal desert could not exist without such interbasin transfers. But the lesson is this: If one builds infrastructure and makes water available, it ensures the growth in population for which you have planned (and then some). It is a self-fulfilling prophecy. But when water availability begins to decline due to climate change or other drivers, it causes water shortages. Areas like the desert Southwest are now vulnerable to declines in precipitation in the Sierra Nevada and mountainous west, much like those in developing countries who depend on glacial snowmelt for their water supplies. Rich countries usually have more options to adapt to changing drivers.

**Climate Change.** The United Nations Intergovernmental Panel on Climate Change (IPCC) issued its Fourth Assessment in 2007, a consensus report from hundreds of scientists in dozens of countries, stating that our climate is changing and it is primarily due to human activities (IPCC, 2007). Currently, the average global temperature is about 0.8°C (1.4°F) warmer than 130 years ago. The warming anomaly is shown in Figure 1 compared to average global temperatures during the period 1961 to 1990. Sea surface temperatures lag the land warming, but are also increasing. Sea surface temperatures are about 0.5°C (0.9°F) warmer, and a warmer sea surface causes increased evaporation. Increased evaporation, in turn, results in more moisture in the atmosphere. Greater moisture in the atmosphere means that global rainfall rates are likely to increase (Wentz et al., 2007).

A warmer sea also causes thermal expansion of the ocean and sea level rise (see Figure 1). Until the past decade or so, the increase in sea surface elevation could be completely explained by the increase in sea surface temperature. But now, meltwaters from Greenland and continental glaciers contribute significantly. Meltwater from Greenland to the Atlantic Ocean in 2007 was approximately equivalent to half the volume of Lake Erie. A warmer planet also causes a decrease in snow cover (see Figure 1), an increase in frost-free soils, longer ice-free periods on northern lakes and the Arctic Ocean, and altered migrations of many plant and animal species.

Satellites have greatly enhanced our global observations of climate. For example, the Atmospheric Infrared Sounder (AIRS) infrared instrument on NASA's Aqua satellite reports significant increases in high clouds (Aumann et al., 2008). NASA models predict that we should expect a 45-percent increase in high clouds for every 1.8°F increase in sea surface temperature; high clouds are often correlated with intense precipitation events.

Globally, it appears that wetter areas are getting wetter, and arid areas are becoming drier. Certainly, intense precipitation events have increased in the eastern half of the United States during the past 50 years (Figure 2). The Upper Midwest now receives about 10 to 20 percent more precipitation than 100 years ago; however,

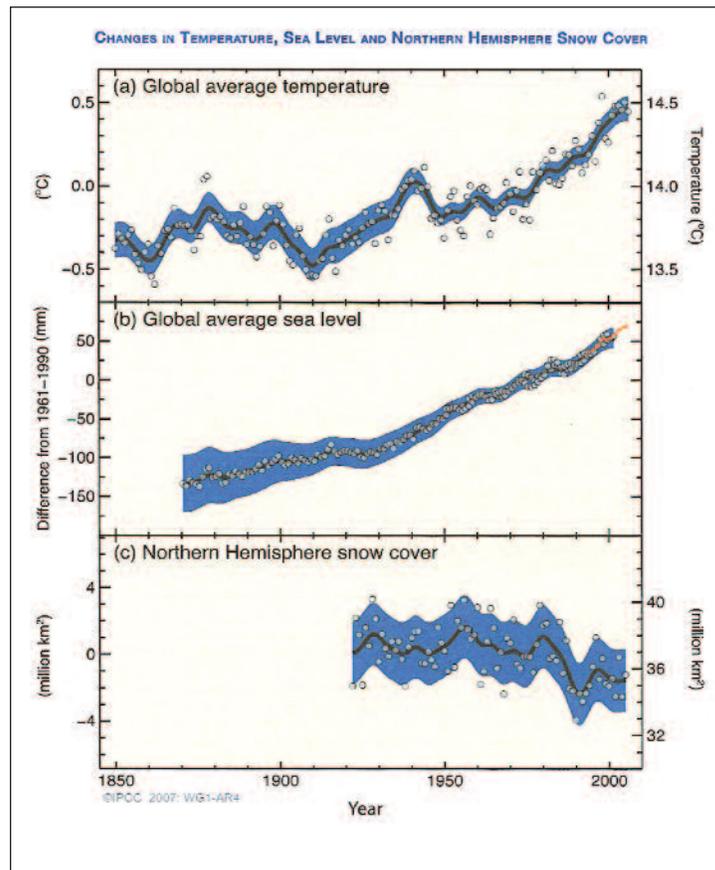


Figure 1. Climate change affects global average temperature, sea level, and snow cover (IPCC, 2007).

runoff (streamflow discharge) has increased even more (Karl et al., 2008). In addition, there is some indication that the timing of large precipitation events is changing with more events in the spring and fall and fewer in the summertime, when crops are canopied. This change means that more rainfall runs off the land with less evapotranspiration than previous patterns. Runoff is more problematic than increasing precipitation because it causes flood events of great economic and social consequence.

The National Oceanic and Atmospheric Administration (NOAA) summarizes the continental weather data in the following way: "One of the clearest trends in the United States observational record is an increasing frequency and intensity of heavy precipitation events ... Over the last century there was a 50 percent increase in the frequency of days with precipitation over 101.6 millimeters (four inches) in the upper Midwestern United States; this trend is

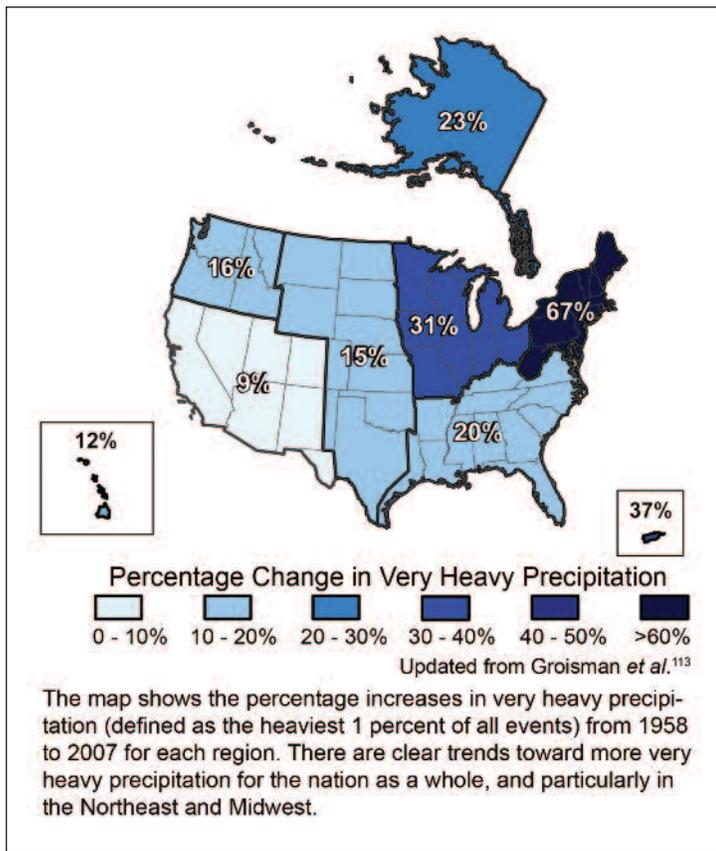


Figure 2. Climate change has regional implications. Shown here is the increase in very heavy precipitation in different regions of the United States. “Very Heavy Precipitation” is defined as the heaviest 1 percent of all events. Image credit: U.S. Global Change Research Program ([www.globalchange.gov](http://www.globalchange.gov)).

statistically significant.” As seen in Figure 2, the northeastern United States is receiving a 67-percent greater frequency of severe precipitation events, and the Midwest is experiencing 31-percent more since 1958 (Karl *et al.*, 2008).

These changing statistics of precipitation and runoff caused Milly *et al.* (2008) to remark, “Stationarity is dead.” *Stationarity* is the scientific term used when statistics are constant (mean, median, variance) through time. But we can no longer count on the mean precipitation – or even on its annual variability – to remain the same. Imagine if someone asked you to live, not on your mean annual salary, but rather on your mean salary plus or minus a large random deviation each year. Overall, you would receive the same amount of money. But some years, you would receive much more than the average,

while others would be extremely lean. That is pretty scary. It is almost impossible to plan for the future in such a scenario. Now imagine that even the random deviation is increasing. Most climatologists are less concerned about the increasing mean global temperature; it is the change in the extremes (the variability) that scares them.

**Land Use Change and Energy Choices.** In addition to population growth, the way we use the land is changing rapidly. People seek to create wealth and develop a better way of life through land resources. In the process, they convert land for agricultural, industrial, and/or municipal uses, which often requires more water or results in the degradation of water quality. Our energy choices – biomass and biofuels, oil, nuclear power, oil shale and tar sands, or clean coal – all have enormous implications for water.

The recent disaster of the BP Deepwater Horizon oil rig in the Gulf of Mexico is a case in point, where a valuable fishery has been jeopardized by one oil well (one out of thousands in the Gulf). On April 20, 2010, BP’s Mississippi Canyon 252 oil well exploded, killing 11 people. The rig sank on April 22. Since then, we have witnessed a series of failed efforts to stop the oil discharge, followed by a flurry of accusations and recriminations by BP, Transocean (the operator of the rig), Halliburton (the contractor employed to expedite the drilling operation), and the United States government. But none of these parties are fully responsible – our addiction to oil is really to blame. This energy choice jeopardizes an entire Gulf ecosystem.

Imported oil is already relatively scarce and expensive (\$50 to \$80 per barrel), so Brazil, Europe, Malaysia, Japan, China, and the United States have adopted biofuels as a strategy for avoiding greater dependence on imported oil. In the United States, the importation of oil is primarily a problem of over-dependence on liquid transportation fuels. If we could curtail our use of oil and diesel for traveling more and more miles in our cars and trucks, we could solve our energy insecurity. Throughout the world, energy security has become almost synonymous with ethanol production from corn, sugar cane, or sugar beets; and biodiesel production from soybean, canola, sunflower, or palm oil.

Biofuels production is not sustainable – at least, not in the way

we practice row crop agriculture to produce the feedstocks for bioethanol and biodiesel in the United States today. Far too many nutrients run off the land, causing eutrophication and Gulf hypoxia (Alexander et al., 2008), and far too much soil erodes for biofuels production to be considered sustainable in the long run. We need a feedstock that is perennial, where tillage is minimized (or nonexistent) and where soils and nutrients are held in place.

Wood wastes, municipal wastes, yard wastes, corn stover, wheat straw, and other non-edible parts of grain crops could be utilized rather than corn in the United States. In addition, perennial crops like switchgrass, miscanthus, sweet sorghum, prairie polyculture, or short rotation woody biomass (poplar, willow), could fill the bill. Tillage is not required for perennials, and deep root systems will hold soil in place, requiring less water.

Switchgrass was originally one of the most ubiquitous prairie plants of the Great Plains and could become so again, enhancing bird habitat and improving water quality while sequestering carbon dioxide into soils. But to utilize the full potential of cellulosic crops, such as prairie grasses, we need improved technology that may still be several years off. Ideally, ethanol should be made from the cellulose in perennial crops and wastes, but it will require developing specialty enzymes to efficiently breakdown cellulose into starch and sugars for fermentation. Both thermochemical conversion and fermentation processes have technological challenges preventing full-scale commercialization.

Are biofuels a panacea for our energy problems? No. Unfortunately, our gluttony for liquid fossil fuels is so gargantuan that we cannot grow our way out of this problem. The United States consumes 21-million barrels of petroleum each day (3 gallons for every man, woman, and child). Even if we utilized all 90-million acres of corn planted in the nation (in 2007) for corn-to-ethanol, it would satisfy only about 15 percent of our current petroleum consumption (National Research Council, 2008). And it would leave us with little corn for food and animal feed (other than dry distillers grains, a byproduct from corn ethanol).

Biofuels are massively land intensive and, in locations where

crops require irrigation, cause huge withdrawals from groundwater supplies. Biofuels do provide some respite from ever increasing oil imports, and Congress has deemed that they are here to stay. The U.S. Environmental Protection Agency's renewable fuel standard (RFS2), published in the Federal Register this year, requires 15-billion gallons per year of conventional biofuels (mostly corn ethanol) by 2015, and a total of 36-billion gallons by 2022, with the difference coming mostly from cellulosic ethanol and advanced biofuels, which release 60 percent less greenhouse gases than the fuel they replace, and which should be much more sustainable in terms of water and soil erosion.

**Global Poverty.** Development professionals recognize that problems of population, climate, environment, and development will never be solved without first addressing global poverty. One-billion people on Earth live on less than \$1 per day – grinding poverty and a daily struggle for water and food. Poverty renders all other actions to mitigate climate or land use change of secondary importance and low priority. Their children are still dying. As long as 0.9-billion people do not have clean drinking water supplies, they will not have the capacity to limit the clearing of forests or exploitation of fisheries.

Will there be enough freshwater for the 9- to 10-billion people projected by 2050? We are already appropriating more than half of the world's freshwater resources for human use (Postel et al., 1996), and the average supply of water per person is decreasing. Although we have made some progress on the U.N. Millennium Development Goals, there are still 900-million people who do not have access to safe drinking water and more than 2 billion who lack adequate sanitation. Millions of children below the age of 5 are still dying from clearly preventable waterborne diseases.

## Impacts on Water Quantity

Given the drivers of global change, exactly what are the impacts? What is not sustainable about our current and projected use of water? Let's analyze some of the impacts these drivers exert on water quantity and quality.

**Too Little Water.** Water withdrawals in the United States have not increased substantially in recent decades. In fact, states like California have continued to gain in population while using less water. Thus, some progress has been made in conserving water, which is encouraging. But the total amount of water withdrawn for agriculture (mostly irrigation water), municipal water supplies, and industrial uses probably is still not sustainable, given the anticipated changes in climate and our inadequate water infrastructure.

In one sense, agricultural withdrawals are the most problematic because water for agriculture is used mostly to irrigate crops and is consumed in the process (consumptive use). It is not returned to the stream or groundwater; rather, it returns to the atmosphere as evapo-transpiration from crops. Of course, atmospheric moisture will eventually form clouds and fall back to earth as precipitation, but it could fall over the ocean or a region that does not need water. About 70 percent of irrigation water is consumptive use, and if it is withdrawn from groundwater or surface water, the resource may be drawn-down unsustainably. Also, roughly 30 percent of the water returned to streams from agriculture (agricultural return flows) is degraded in quality due to the accumulation of nutrients, soil particles, pesticides, minerals, and salts during the process.

Areas of brown in Figure 3 indicate water withdrawals of 250 to 2,500 millimeters of water (9.84 to 98.4 inches) averaged over the entire county mapped. In other words, it would require precipitation of that amount falling every year throughout the county simply to supply the water being withdrawn for use. Areas of the country with high water withdrawals fall into one of four possibilities: 1) withdrawals from water-rich areas with high precipitation; 2) withdrawals from water-poor areas experiencing periodic scarcity; 3) withdrawals from areas with interbasin transfers of water to augment the supply; or 4) withdrawals from areas “mining” groundwater to augment the supply. Except for the first possibility listed, none of the situations are sustainable in the long-run, given the shifting climate, land use, population patterns, and energy choices occurring.

Dividing the total water withdrawals by the average precipitation

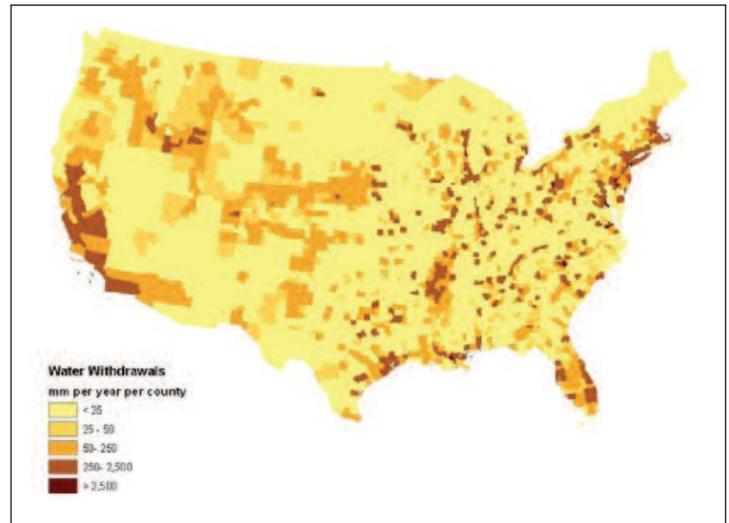


Figure 3. Total water withdrawals (from agriculture, municipalities, and industry) in the United States by county (Hutchinson, 2008).

falling on each county, one arrives at a simple measure of water stress. A ratio of withdrawals/precipitation greater than 1.0 indicates critical water stress, an unsustainable situation in the long run. The areas of the country where this is true (mapped in colors of orange and red) are shown in Figure 4 (Hutchinson, 2008). As we might expect, the desert southwest portion of the country is withdrawing more water than falls on their “footprint.” It is caused by withdrawals for municipal water supply to serve millions of people in an arid area, and by withdrawals for agriculture to grow crops for food and animal feed.

More surprising and interesting is the “pock-marks” across the entire nation, as shown in Figure 4. Water stress is not only a problem in the desert Southwest, where we might expect it; rather, it is a problem in isolated areas throughout the nation. There are many locations where people are withdrawing more water than falls on their footprint. Again, this ability is made possible by interbasin transfers or by groundwater mining, and it leaves us vulnerable to changes in population, climate, and land use.

**Too Much Water.** We can also have too much water. While areas of water stress are pointed out in Figure 4, some of those same regions periodically experience flooding and serious social disruption. Consider the heart-wrenching floods in Rhode Island and Nashville,

Tennessee, this year. In addition to the loss of life from storms and flooding, many businesses go bankrupt or leave the area, never to return. Witness the long recovery in New Orleans following Hurricane Katrina (and the lack of recovery 5 years later in the Ninth Ward of New Orleans).

I know a little about the suffering of those communities based on our own experience in Iowa with the floods of 2008. The Cedar River reached unprecedented levels of discharge during June 2008, and Coralville Reservoir (Iowa River) was over-topped and flooded Iowa City and the University of Iowa. Official damage to the University of Iowa was \$741 million, and we still have several departments (Music, Art, Drama, and Performing Arts) without permanent academic homes. Worse still was the town of Cedar Rapids, just 25 miles north, where damage estimates ranged \$7 billion (the fifth worst natural disaster in the nation's history) and recovery of the Czech Village and African American Museum, located in low-lying areas along the Cedar River, are still in doubt.

Somewhere in the world, there is always flooding. But what is new is the frequency of severe precipitation and flooding caused by increased sea temperatures and global rainfall rates (IPCC, 2007;

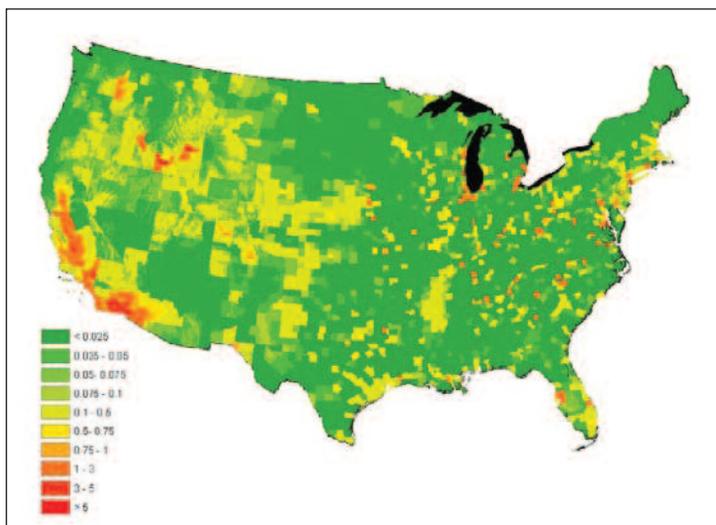


Figure 4. Water stress as defined as the ratio of total water withdrawals to precipitation falling on each area in the United States by county. A ratio of 1.0 indicates that the area is withdrawing more water than falls on their footprint, which is only possible by interbasin transfers of water or mining of groundwater resources (Hutchinson, 2008).

Wentz et al., 2007). The statistics of flooding are shifting, and it will stress the social and economic fabric of society (Milly et al., 2008).

Eventually, we need to mitigate greenhouse gas emissions and transition from the fossil fuel age to renewable energy sources and energy efficiency. Responding to climate change offers an enormous economic opportunity and an engine for creating green jobs in the future. As a part of this transition, we should reinvent our water infrastructure to be smarter, more reliable, resilient, and self-repairing.

We must *adapt* to a changing water future. If floods and droughts are becoming more frequent, we must evolve our infrastructure to deal with it. We cannot allow developers to hold sway over city councils and county zoning commissions. We cannot continue to build in the 500-year flood plain, and our water and energy systems must be made immune to the vagaries of a changing climate.

## Impacts on Water Quality

**Agriculture.** One of the gravest impacts on water quality today is from high-input agriculture. Like greenhouse gas emissions (GHGs), the runoff of nutrients, soils, and pesticides from modern agriculture is a classic failure of the free market to internalize environmental costs into the price of the product. In the case of GHG emissions, these costs are associated with using the atmosphere and returning to it gases, which warm the earth. In the case of agriculture, the costs are associated with allowing runoff to degrade water quality for aquatic life and downstream users.

In Figure 5, the nitrogen and phosphorus yields to the Mississippi River Basin are due largely to modern agriculture in the central United States (Alexander et al., 2008). Nitrogen loads are in excess of 1,000 kilograms per square kilometer per year ( $\text{kg}/\text{km}^2\text{-yr}$ ) in the Corn Belt of the Midwest, representing 5 to 10 percent of the nitrogen applied to corn and a significant economic loss for the farmer. But it also impairs downstream uses all the way from the farm to its ultimate discharge in the Gulf of Mexico. The Mississippi River discharge causes hypoxia (i.e., waters with less than 2 milligrams per liter of dissolved oxygen) during July-October in the Gulf that

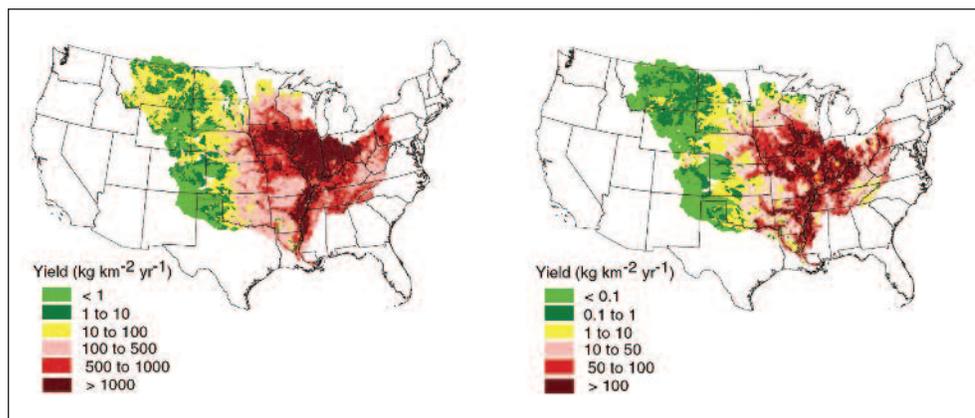


Figure 5. Nitrogen load (left) and phosphorus load (right), which is delivered into streams and rivers from mostly agricultural sources in the Mississippi River Basin (Alexander et al., 2008).

threatens shrimp, crab, and oyster fisheries over an area of 20,000 square kilometers.

In the watershed, nutrient runoff causes over-fertilization of surface waters, changes in habitat for biota, loss of species, excessive algal and plant growth, loss of transparency in the water column, and taste and odor problems for drinking water supplies. Such impairments in water quality not only cause stress on aquatic ecosystems, but also exacerbate the quantity of water available for surrounding communities. For example, in Iowa, many towns and cities are making greater use of groundwater aquifers for municipal water supply because they want to avoid problems associated with nutrient and pesticide runoff from agriculture in surface waters. Over time, this use causes drawdown of the groundwater aquifers. Thus, a water *quality* problem (agricultural runoff) creates a water *quantity* problem by utilizing groundwater at rates greater than their recharge.

**Energy Choices and Land Use Change.** A more recent development affecting both water quality and quantity is the production of biofuels. In 2007, Congress passed the Energy Independence and Security Act, which mandates 36-billion gallons of biofuels to be produced in the United States by 2022. The incentive is to produce 15 percent of our transportation fuels from home-grown crops, thus lessening our dependence on foreign oil. Secondly, there is a need to reduce greenhouse gas emissions for climate control, and biofuels production facilities coming online in

the future must perform much better than the petroleum-derived products being replaced.

In general, there is a tight interconnection between energy production and the use of water resources, whether it is the production of oil from tar sands, use of cooling water for nuclear power, coal liquefaction or gasification, or recovery of natural gas from coal-beds. Energy production frequently uses

considerable quantities of water and/or degrades the quality of return water. The choice to produce biofuels and, in particular, the use of corn as a feedstock to make bioethanol has large implications for both water quantity and quality (NRC, 2008).

Corn requires considerable water to grow the crop, whether the water comes as irrigation from groundwater (so-called “blue water”) or from direct rainfall (“green water”). Irrigation water is largely consumed by evapo-transpiration, but an equivalent volume of green water is used in rainfed agriculture. The impact comes when irrigation water is taken from groundwater in arid areas like the High Plains Aquifer, stretching from South Dakota to the panhandle of Texas (Figure 6). The High Plains (or Ogallala Aquifer) is the largest unconfined aquifer of its kind in the country, roughly equal in volume to Lake Huron. But it is being drawn-down unsustainably at rates much faster than its rate of recharge.

The locations where bioethanol facilities are located in the United States are shown in Figure 6. Mostly, these facilities are built in corn-growing regions, so the production plant is near the feedstock crop. This set up presents some infrastructure problems in getting the product, bioethanol, to the densely populated areas where people need it. In the eastern half of the country, rainfed agriculture is used to grow the corn. In the West, irrigation water, mostly from groundwater, is utilized. About 2,000 gallons of water are required per bushel of corn in the High Plains region of Nebraska, and 4,000 gallons of water per bushel in the Central Valley of California (National Research Council, 2008). At production rates of 2.8 gallons

of ethanol per bushel of corn, this amounts to approximately 700 gallons of water to produce a gallon of ethanol in Nebraska, and 1,400 gal/gal in California. Filling up your flex-fuel car with 10 gallons of corn-ethanol requires about 7,000 gallons of water to produce the feedstock in Nebraska. Large volumes of water are required also to grow the crop from rainfed agriculture, but it does not result in the “mining” of water from groundwater.

In addition to the water required to grow the crop, bioethanol requires significant quantities of water for the fermentation process to produce the fuel. On average, each black dot on the map requires 4 gallons of water from surface or groundwater supplies for every gallon of ethanol produced at the facility. In the Midwest, water is taken mostly from confined glacial aquifers, which may stress an already overused resource and draw water out of storage much faster than the rate of recharge.

Agricultural and municipal withdrawals in Nebraska have resulted in decreased groundwater elevations in the Ogallala

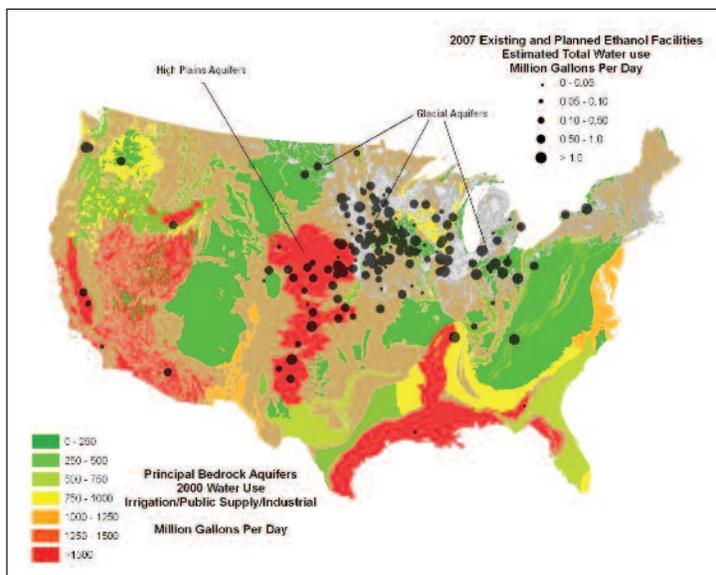


Figure 6. Ethanol biofuels facilities (black dots) superimposed on a map of the major bedrock aquifers and their water usage rates. Corn for ethanol feedstock in the area of the High Plains Aquifer and Central Valley of California require irrigation water to grow the corn. Ethanol plants located in glacial (confined) aquifers also require groundwater withdrawals to produce the ethanol. Figure was reprinted with permission from the National Academy Press, 2008, National Academy of Sciences.

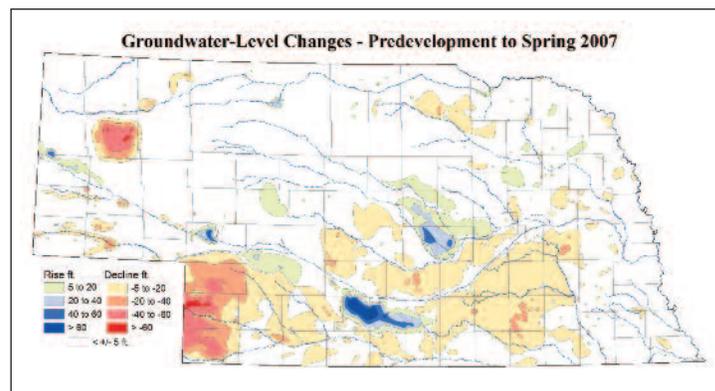


Figure 7a. Groundwater drawdown in the surficial aquifer (High Plains Aquifer) in Nebraska due to agricultural and municipal withdrawals. Image credit: Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Aquifer, as shown in Figure 7a. But that is not the only unsustainable “mining” of groundwater occurring in the United States. In areas of the Midwest (Iowa, Minnesota, Southern Wisconsin, and Illinois), municipalities and industry have been withdrawing water since pre-settlement times (late nineteenth century). Often, these withdrawals come from confined aquifers that are relatively easy to pump-down. The water comes out of storage and depressurizes the aquifer (loss of pressure head). Examples of this phenomenon include the Jordan Aquifer in Iowa (Figure 7b) and the Cambrian-Ordovician Aquifer near Chicago, Illinois, and Milwaukee, Wisconsin (Figure 7c). These aquifers have been drawn-down an incredible 300 feet and 800 feet, respectively. They serve as poignant reminders of water unsustainability.

## What Can We Do?

What can we do to meet the challenge? First, we must recognize the cause of the problem and seek to *mitigate* the drivers, where possible. Second, we must seek to *adapt* to a changing water environment. In the engineering community, we can help communities make better choices about water resources, and we can design water infrastructure that meets the needs of people in a changing water environment. In the scientific community, we must elevate our science to enable better monitoring, modeling, and

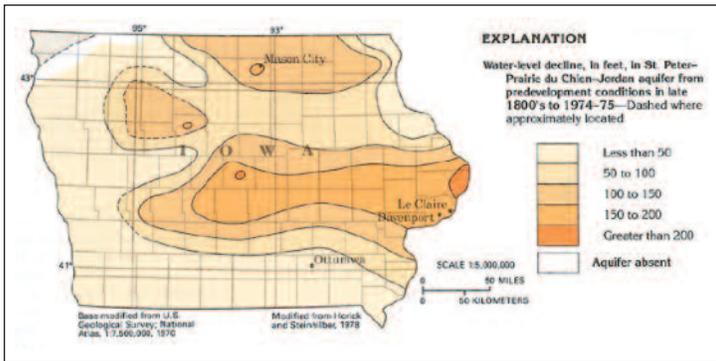


Figure 7b. Drawdown of confined Jordan Aquifer in Iowa due to municipal and industrial withdrawals. Image credit: U.S. Geological Survey (1992).

forecasting of our water future, so stakeholders and decision makers have better information upon which to act.

We can improve the water sustainability of agriculture by insisting on Best Management Practices (BMPs) from agricultural nonpoint sources. Otherwise, these discharges should undergo a permitting system similar to wastewater treatment plants. Nonpoint sources remain the largest source of nutrient over-enrichment and water impairment in the country, and it is time to make

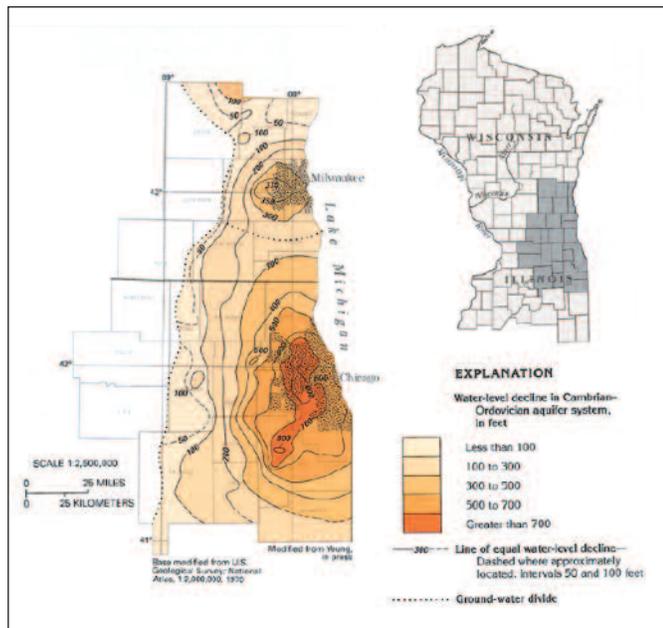


Figure 7c. Drawdown of confined Cambrian-Ordovician Aquifer in the vicinity of Milwaukee and Chicago by municipal withdrawals. Image credit: U.S. Geological Survey (1992).

improvement. Farmers and ranchers will need incentives for BMPs, which can be accomplished by switching existing farm programs from crop subsidies to environmental payments with clearly defined numerical goals. We will use perennial crops, less irrigation water, less fertilizers and pesticides, and targeted watershed improvements. No-till agriculture, contour plowing, buffer strip installation, created wetlands, crop rotation, intercropping, grass stripping, and phytoremediation of degraded lands will become the norm.

Our unsustainable water use is myopic in how we view and manage water. We permit wastewater discharges, for the most part, without regard to downstream uses (e.g., water supply or a protected fishery). We ignore nonpoint sources without considering their impacts on allowable point source discharges. We allow agriculture to mine groundwater resources irreversibly. Interstate rivers frequently have different water quality standards on each side of the same water body. Jurisdictions are complicated and overlapping, and no one is managing water in a holistic manner. Government agencies do not manage river basins in their entirety, including both groundwater and surface water resources. Surprisingly, no agency is responsible for tracking the total volume of water resources in the country. The U.S. Geological Survey’s gauging network accounts reasonably well for flow in streams and rivers. But the water contained in snowpack, soil water, lakes, and groundwater reservoirs is mostly unaccounted for. Our water management structure is fragmented and separated from analysis of the entire water cycle.

**Water Cycle Engineering.** I remember as a graduate student at the University of Texas in the early 1970s that my fellow students would identify with only a portion of the water cycle. They would proudly announce, “I’m a wastewater engineer,” or “I’m a drinking water treatment engineer,” or “I’m a water quality specialist.” But I tell my students who are so inclined today, “No, you are all water cycle engineers.” After all, drinking water is returned to streams as wastewater. And wastewater is recharged to aquifers, either purposefully or inadvertently. And we withdraw from aquifers our drinking water supply, thus, completing the cycle (Figure 8). It is all part of one water cycle.

Water reuse is practiced today inadvertently, whether people want to admit it or not. By the time the Trinity River in Texas reaches the Gulf of Mexico, it is mostly wastewater. Downstream withdrawals from the river for drinking water purposes utilize (for the most part) treated domestic sewage. In practice, our water reuse is of three types:

- Inadvertent potable reuse.
- Indirect potable reuse.
- Direct potable reuse.

Indirect potable reuse is the practice of reusing treated domestic or industrial wastewater by discharging it to a reservoir or aquifer for the purpose of later withdrawing it and using it as a water supply. The supply is normally treated prior to consumption to bring it to drinking water standards. Direct potable reuse, on the other hand, is introduction of recycled water directly into a potable water distribution system downstream of a water treatment plant

Aquifer storage and recovery and groundwater recharge are practiced as a form of indirect potable reuse in the United States today, including Southern California, Las Vegas, and Southern Florida. The South Florida Water Management District oversees the operation of dozens of injection wells that recharge aquifers with treated wastewater. Each region of the country has special issues, both technical and social. We are ignorant of the basic behavioral science on how we use water and how we might encourage people to conserve its use. What education, regulations, or financial incentives are necessary to induce us to modify our behavior? Under what circumstances can we gain public acceptability to reuse wastewater as drinking water? Engineers should work closely with social and behavioral scientists to understand the answers to these questions.

Some people think we do not need to worry about drinking water supplies because we can always desalinate seawater. But this is a myth that bears closer scrutiny. Desalination on a massive scale will require huge amounts of energy and will generate enormous volumes of brine.

A case in point is Singapore. Singapore is a city-state of 4.6-million people who catch and use every drop of precious water that falls on

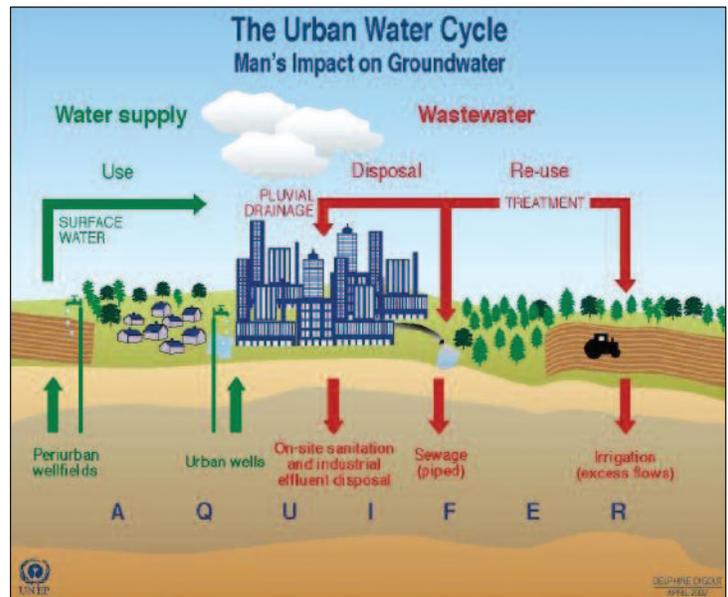


Figure 8. Drinking water supply, wastewater treatment, and discharge are all part of the overall water cycle (United Nations Environment Programme/GRID-Arendal, 2002).

their island. Still, they need to import about half of all their water supply from Malaysia. In the face of such water insecurity, Singaporeans made a plan 20 years ago to build a water industry that would be a model for the world while, at the same time, solving their own water shortage. They planned to build five new desalination plants using brackish groundwater or seawater as a source, but a funny thing happened on their way to water independence. They discovered it was far cheaper to reuse wastewater (both industrial and domestic) and to treat it thoroughly to drinking water standards, rather than to employ the desalination of seawater. A process of low-pressure membrane microfiltration followed by high-pressure reverse osmosis and, finally, ultraviolet disinfection does the trick.

In the future, nations will routinely reuse wastewater through advanced treatment and aquifer storage and recovery, while employing both direct and indirect potable reuse. In Figure 9, a group of “so-called water professionals” partake of treated domestic sewage and industrial wastewater. They are practicing direct potable reuse. For the most part, the Singapore government has been deft at educating the public about the importance of water reuse and in

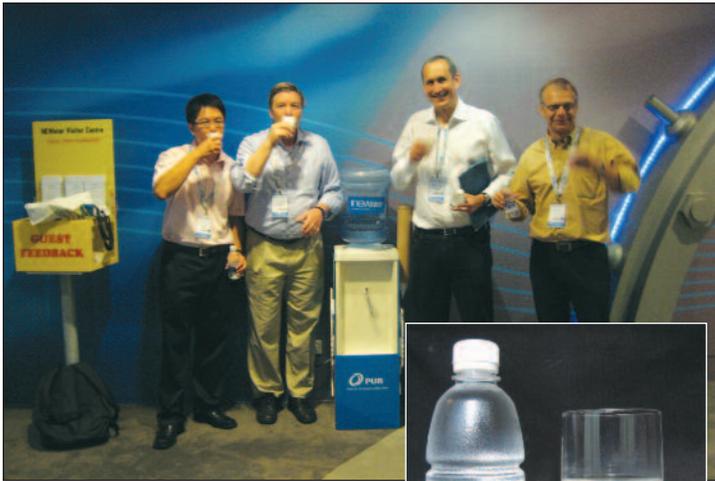


Figure 9. Drinking a cool glass of (treated) domestic sewage at the NEWater water reuse treatment facility in Singapore (top) and the bottled NEWater product (right). From left to right: Yi-Pin Lin, Jerry Schnoor, Pedro Alvarez, and Mark Wiesner (photos courtesy of Jerry Schnoor).

packaging their product to gain public acceptability (NEWater product, see Figure 9). As a result, Singaporeans practice indirect potable reuse with excellent public support and are prepared to practice direct potable reuse, if the need arises. Careful management of the entire water cycle is the key to husbandry of this precious water resource.

**Water Infrastructure.** Singapore has invested heavily in their water infrastructure because it is such a high priority, and the investment has paid off. They are now an international “hydro-hub,” having solved most of their own water problems, created new jobs in a high-technology industry, and exported their water technology (membranes, disinfection, design) to others.

Unfortunately, the same cannot be said for water infrastructure in the United States. Most of our infrastructure in the West and Southwest is struggling to catch up to the increasing populations migrating there. On the other hand, most of the eastern half of the United States has decrepit water infrastructure (over 100-years old), such as combined sewer systems and outdated water distribution networks that are badly in need of repair or replacement. The American

Society of Civil Engineers (2009) estimates the capitalization required to modernize infrastructure in the United States has grown to \$2.2 trillion, a large fraction of the nation’s overall annual budget.

**Mitigation and Adaptation.** Global climate is already changing. Regional trends and differences are becoming evident, such as greater precipitation events in the Midwest and Northeast. Snowmelt in the Sierras is occurring earlier, with a danger of not lasting through the growing season. Obviously, it is important to *mitigate* climate change because the overall social and economic costs are enormous.

In the past 60 years, global population has increased from 2.5 billion to 6.8 billion; we have added 75 parts per million by volume to the carbon dioxide concentration of the planetary atmosphere (a 27-percent increase over pre-industrial levels); the pH of the entire ocean has decreased from 8.2 to 8.08 (a 32-percent increase in hydrogen ion concentration); and the temperature of the earth’s surface, including the oceans, has increased about 0.5°C (an enormous storage of heat). That is why polar ice is melting, Greenland and Antarctic ice sheets are breaking-up, continental glaciers are disappearing, and thousands of plant and animal species are struggling to move to higher elevations and latitudes.

We cannot withstand 60 more years like the last. What is at stake is nothing less than the habitability of our coastlines, the water supply for millions of people depending on glacial melt water, the health of our ocean fisheries and coral reefs, the ability to recover from more frequent floods and droughts, and the overall economy of our people. The economy really is about the environment, after all. The environment is too big to be allowed to fail.

If there is any benefit from the Great Recession, it is that “regulation” is no longer a dirty word. Although cap-and-trade and market forces may be a part of mitigating our GHG emissions, I am increasingly convinced that a combination of a carbon tax and command-and-control regulations against GHG emissions is the fastest, most direct, and fairest approach to mitigation.

Where we anticipate an inability to meet climate goals, we must plan to *adapt*. We must overcome the temptation to develop in flood

plains, on barrier islands, in fire-prone forests, and atop sea-cliff vistas. In my own state of Iowa, following the floods of 2008, Cedar Falls passed a trendsetting resolution against developing in the 500-year flood plain. This restriction is prudent because the frequency of severe storms and flood events is increasing in the Midwest, and Cedar Falls is taking proper precaution against future loss of life and property. If one must build in a floodplain, the building should be “flood-proof” and designed to be easily operational following flood-water inundation. We must become accustomed to living with floods.

Water sustainability requires resolute political will and translates into the successful adaptation to a changing water environment. We need resilient water infrastructure – water treatment plants that do not succumb to high waters, that report their own mistakes, and that return online themselves after brief interruptions. Wastewater plants will be more decentralized, and will not overflow and bypass raw sewage with the smallest storm. Such technologies and policies will protect our people and our water, and they will create green jobs.

**WATERS Network.** Smart infrastructure and planning requires superior hydro-informatics, modeling, and forecasting. In the United States, we do not have a single major river basin model operating in real-time to provide estimates and forecasts of water quality. We cannot tell shrimpers in the Gulf Coast what magnitude or location of Gulf hypoxia to expect; we cannot warn tourists along the coasts about serious red tide outbreaks; and we cannot alert water plant operators about *Giardia* pathogens coming downriver. We need to better understand the fate and transport of water contaminants to inform policy decisions regarding the application of agricultural fertilizers and pesticides, the use and discharge of pharmaceuticals, and the allowable draw-down of groundwater. We need national models of rivers and aquifers to make more informed, real-time management decisions in the event of toxic chemical spills or terrorist threats. An ability to analyze and forecast water quality and quantity problems would be a major benefit to the nation and would improve the operation, design, and development of the next generation of water infrastructure needed.

A schematic of a proposed real-time monitoring, modeling, and

forecasting network at the river-basin scale is included in Figure 10 (WATERS Network, 2008). Here, the goal is to put “humans in the loop” and to analyze not only the natural hydrologic cycle, but the ways in which humans affect and limit water resources. Water engineers must work with many other disciplines to analyze such problems – not any single discipline alone can do it. WATERS Network would lead to a better understanding of the physics, chemistry, and biology of natural waters, and to the human dimensions of how we make decisions about water use and policy.

Recent breakthroughs in wireless and broadband technologies, sensors, and high-performance computing make possible such a network. An observatory with nested sensors could be located in each major river basin of the country to characterize the hydroinformatic

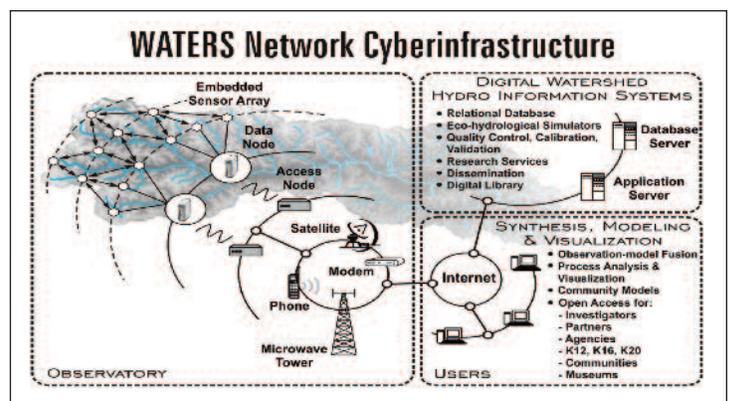
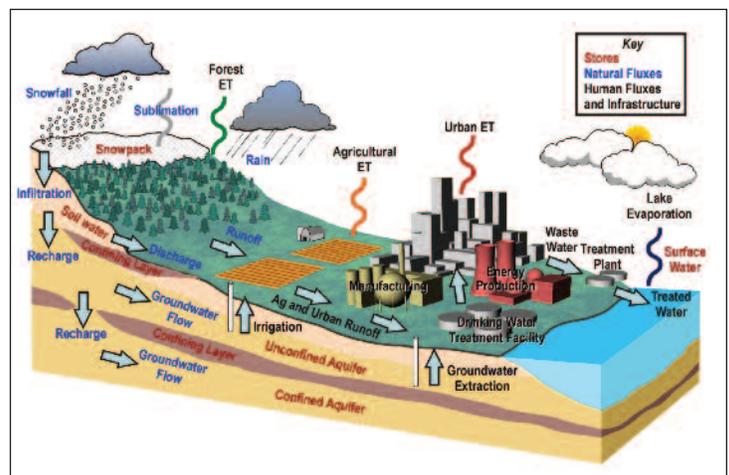


Figure 10. Schematic of a highly instrumented Waters Observatory for the monitoring, modeling, and forecasting of water quality and quantity within a large-scale basin (top); and the cyberinfrastructure for the hydroinformatics and community modeling enabled by such an observatory (bottom) (WATERS Network, 2008).

continuum and the scaling-phenomena from small streams to major rivers. Mathematical models would be operated in real-time, assimilating streaming data from satellites, aircraft missions, gauging stations, in-field sensors, and groundwater monitoring devices. The models could “fill in” areas of the country where sensors are not located by making use of an intelligent digital database (Hydrologic Information Systems). Analysis would include a domain stratification of the nation’s water resources to recognize similarities of physico-chemical and human-impacted characteristics of river basins. Hundreds of millions of dollars would be needed to invest in just the cyberinfrastructure for such a prototype network, but it would enable the science and engineering for water sustainability in a changing world.

One aspect of the WATERS Network that is most appealing is the idea of using “citizen scientists,” volunteers from kindergarteners to adults, to ground-truth sensors and remotely-sensed data. Simultaneously, we would educate volunteers to analyze water samples accurately, while at the same time create advocates for the environment and (perhaps) encourage more students to become environmental scientists. A sizable amount of literature attests that data collected by citizen volunteers is as high of quality as that obtained by professionals with the same equipment.

I have a dream that tomorrow at noon children in every country will walk to a creek, stream, or lake nearest to their school and record a scientific observation – measuring the temperature, transparency, pH, or dissolved oxygen at their site. Millions of students already have “smart phones,” and their phones are already equipped with Geographical Positioning Systems (GPS) and include open data ports for simple sensors. The students will upload their data report via the Internet and, the next day, will collectively publish a map of the world’s water quality. Even the temperature of millions of streams in the world would be an incredible scientific accomplishment. Hopefully, the volunteers would think about the science behind their measurement and would vow to improve the environment, where needed. These volunteers would constitute a network of “water watch dogs” for the entire planet – geopolitics is transcended by such endeavors.

**Millennium Development Goals.** In the year 2000, delegates from 189 countries met in New York to formulate the Millennium Development Goals, eight actions deemed necessary to improve human suffering on planet Earth. The goals were adopted by all nations, with a target period of achievement of 15 years in 2015. We are more than two-thirds of the way to the target year, and the Millennium Development Goals are far from accomplished. To be sure, some progress has been made, but some goals are sorely lagging. Goals related to income growth, AIDS, education, and women’s rights have made the most progress. But goals concerning water sanitation and health have not fared so well.

It is the seventh goal (ensuring environmental sustainability) that water engineers and scientists identify with most strongly. Nearly half of humanity faces a scarcity of water (Figure 11); one in four people are without proper sanitation; and women continue to carry the greatest burden of collecting water. To date, the number of people without access to safe drinking water has decreased from 1.1 billion to 900 million. But this progress is still far from the goal of halving the number by 2015.

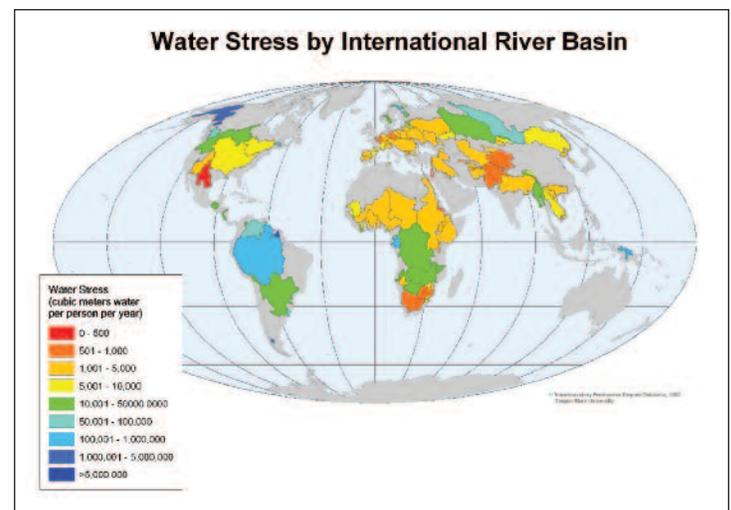


Figure 11. Global Water Stress for major international river basins. The United Nations Environment Program recommends available water greater than 1,700 cubic meters per person per year be available from the river basin. This image is the product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at [www.transboundarywaters.orst.edu](http://www.transboundarywaters.orst.edu).

It is sobering to think that these water and sanitation goals are among those with the least progress because they are ones that we know best how to conquer. They are the goals that directly relate to environmental engineering and science and to the constituency of the National Water Research Institute. We know how to provide proper water and sanitation in the developed world, but it is the challenge of underlying poverty that makes success so difficult.

Nothing makes me prouder today than the interest and dedication of our students toward these Millennium Development Goals. Despite the difficult economy in which we find ourselves, our students are donating their time and talents to help in developing countries. In most cases, their role is to simply listen, learn about the problems, and leverage and empower the people in that country. Most frequently, the villagers know what needs to be done – they simply lack the capital to invest and the contacts of how to bring it about. Our students multiply the villagers’ power by bringing dollars, manpower, and partner non-governmental organizations (NGOs) to the table. Engineers Without Borders and Engineers for a Sustainable World are meeting the challenge of water sustainability one location at a time, and they are benefiting themselves far more than the locals.

### Summary

**Water sustainability:** *The continual supply of clean water for human uses and for other living things.*

Like the Millennium Development Goals, water sustainability is an elusive goal that we can probably never reach completely. Perhaps it should be viewed as a “stretch goal” for which we strive and measure our progress along the way. One of the clear messages of this lecture is that we should consider our water resources more holistically and the water cycle in its entirety rather than parts of a fragmented tapestry. Another theme is that we can always do better, and continuous improvement of our water sustainability is within our reach. Changes in our water environment due to population growth and migration, climate change, land use and energy choices, and poverty make water sustainability a moving target. Changes in

these drivers can be planned for *a priori* if we improve our ability to monitor, model, and forecast water resources.

Although I am an engineer, I do not consider myself a technological optimist. I do not believe that technology alone will solve the problems of water, climate change, or energy resources discussed in this lecture. To be sure, technology can and will play a role through smart water infrastructure, renewable energy sources, and energy efficiency. But to accomplish the goals associated with this lecture, we must begin to view the billions of people in future generations as our family and take responsibility for their livelihoods. Our profession, our government, and our multinational organizations need to evolve much faster than the changing environment witnessed today.

It will require a bold, new form of leadership that we have not seen on the planet to date. Our population is growing too large, but our tribe is too small. We could better accommodate the numbers if we had a different world view. Our own livelihood depends on each other, and our common future demands a visionary viewpoint. This argument is not legal or technological; it is one of morals and ethics and spirit.

### Acknowledgments

I would like to thank Professor Keri C. Hornbuckle, Chair of the Department of Civil and Environmental Engineering at the University of Iowa, for nominating me; the Clarke Prize Executive Committee of the National Water Research Institute for selecting me for this incredible honor; and the Joan Irvine Smith & Athalie R. Clarke Foundation for making the Clarke Prize possible. It is a humbling experience to be chosen from so many excellent candidates and to be distinguished by the company of truly world-class scientists and engineers selected as past Clarke Prize recipients.

I would also like to thank the University of Iowa and the Center for Global and Regional Environmental Research, which made possible my exploration into water sustainability, and the Water Science and Technology Board of the National Research Council, National Academies of Science, for allowing me to become invested in the water implications of biofuels.

This lecture would not have been possible without the collaboration of colleagues at the WATERS Network Project Office, funded by the National Science Foundation. In particular, Barbara Minsker, Jeff Dozier, Richard Hooper, John Braden, Jeanne VanBriesen, Charles Haas, Roger Bales, Tom Harmon, Claire Welty, David Tarboton, Nicholas Clesceri, Patrick Brezonik, and Bruce Hamilton. My colleagues Craig Just, Marian Muste, Nikolaos Nikolaidis,

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The 2010 Clarke Prize Honoree

## JERALD L. SCHNOOR, PH.D.

Environmental engineer Jerald L. Schnoor, Ph.D., was selected as the seventeenth recipient of the NWRI Athalie Richardson Irvine Clarke Prize because of his leadership and impact on promoting the sustainable use of water.

Dr. Schnoor is the Allen S. Henry Chair of Engineering at the University of Iowa. He also co-founded and co-directs the university's Center for Global and Regional Environmental Research, which is a state-funded institute devoted to studying and bettering our environment.

To ensure water use sustainability, Dr. Schnoor has focused much of his career on improving human management decisions to reduce negative impacts on water. For instance, he developed models of the complex chemistry of acid rain and its impacts on aquatic systems and watersheds. He played a central role in linking acid rain to lake acidification, which ultimately resulted in his "Trickle Down" model being adopted by the U.S. Environmental Protection Agency and later used to guide the 1990 Clean Air Act Amendments.

Dr. Schnoor was also one of the first researchers to investigate using plants to take up toxic organic chemicals and other pollutants (a process known as "phytoremediation")

as a means to remediate contaminated hazardous waste sites – fostering a new green technology for the treatment of soil and groundwater.

Among his recent work, Dr. Schnoor chaired a National Research Council committee on the "Water Implications of Biofuels Production in the United

States," which noted water quality and availability problems associated with increasing ethanol production from corn.

He was also selected as Co-Director for the National Science Foundation Project Office on the WATERS Network, a \$300 million proposal to construct a national environmental observatory network for sensing, modeling, and forecasting water and contaminants.

An intellectual leader in the world of scientific publishing, Dr. Schnoor also serves as Editor-in-Chief of *Environmental Science & Technology (ES&T)*, the leading journal in the world on environmental engineering and science. 



The  
ATHALIE RICHARDSON IRVINE  
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*for Outstanding Achievement  
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*The 2010 Clarke Prize Lecture, Water Sustainability in a Changing World, by Jerald L. Schnoor, Ph.D., was first presented on Thursday, July 15, 2010, at the Seventeenth Annual Clarke Prize Award Ceremony and Lecture, held at Leatherby's Cafe Rouge in the Renée and Henry Segerstrom Concert Hall at the Orange County Performing Arts Center in Costa Mesa, California.*

*The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize outstanding research scientists who have demonstrated excellence in water science research and technology. Dr. Schnoor was the seventeenth recipient of the prize, which includes a medallion and \$50,000 award.*

*The Clarke Prize was named after NWRI's co-founder, the late Athalie Richardson Irvine Clarke, who was a dedicated advocate of the careful stewardship and development of our water resources. Mrs. Clarke's daughter, Mrs. Joan Irvine Smith (also an NWRI co-founder), is patron of the award.*

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