

The *Athalie Richardson Irvine Clarke Prize for Outstanding Achievement in Water Science and   
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**Foreseeing Unintentional Water Consequences that  
Affect Human and Ecosystem Health**

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Engineers have developed technologies that have transformed society, increased life expectancy, and enriched life through learning and innovation. Some of the most transformative technologies for human health are in the areas of food, energy, and water. However, many of these technologies—including drinking water treatment—have unintended environmental and human health consequences, many of which exhibit unique geospatial impacts and implications.

Environmental engineers strive to develop new technologies to provide water that meets or exceeds drinking water regulations. But unintended consequences stem from some of these technological solutions. This retrospective analysis offers ideas about how our profession can be more proactive in protecting public health by foreseeing potential consequences.

**Transformative Engineering Achievements and Unintended Consequences**

The Haber-Bosch process enabled people to capture nitrogen from the atmosphere to create fertilizers, helped expand agricultural output, and improved human nutrition. Bringing electricity to communities is directly proportional to GDP, and it helps people to read and learn after dark and to connect to the world through social media. Chlorination of drinking water is often credited with increasing life expectancy throughout the early 1900s, and has nearly eradicated typhoid fever and other waterborne diseases where the technology is used.

Each of these transformations have had unexpected local and regional effects on aquatic ecosystem and human health, for example:

* Fertilizer overuse and runoff causes eutrophication and affects fish migration and estuary health (hypoxic zones) from Monterey Bay, California, to the Everglades and Mississippi Delta.
* The increased use of fossil fuels to meet electrical demands generates greenhouse gases that disproportionately affect different parts of the world by altering precipitation/runoff patterns, increases the number and intensity of hurricanes, and causes sea level to rise.
* The discovery of spatial patterns of *Cholera* in 1854 London brought about the chlorination and filtration technologies that have allowed cities to grow, creating *megacities* that consume vast global resources. Megacities can financially and politically disenfranchise billions of people who live outside of these commercial and social hubs.

Perhaps these consequences and trade-offs are worthwhile, as society advances. But were they foreseeable? As other new technologies such as artificial intelligence rapidly transform society, do engineers have the tools to foresee unintended consequences that could affect our water systems?

**Disinfection Trends Have Created Spatially Variable Water Quality**

Disinfection significantly reduced acute human health risks due to waterborne disease, but by the 1970s, scientists understood that safety comes with some risk, including the formation of carcinogenic disinfection byproducts (DBPs). Reducing chronic exposure to DBPs emerged as a balancing act with protecting people against acute waterborne diseases. More recent work suggests that DBPs could have acute health risks to sensitive populations, for example, pregnant women.

By the 1980s, DBPs and pathogen disinfection were regulated, and by the early 2000s, the tightening of DBP regulations began to limit the use of free chlorine. The water industry had two options: Utilities could deploy granular activated carbon or membranes to remove organic DBP precursors, which has high capital and operating costs; or, utilities could reduce levels of regulated DBPs by switching from free chlorine to chloramines.

Today in the United States, over half of the population is served water that is treated with chloramines. Chloramines treatment was the less expensive option to reduce regulated DBPs, but it has become clear that a larger percentage of unknown and unregulated DBPs form with chloramines compared to free chlorine. Many of the nitrogen-based DBPs (N-DBPs) are more geno- and cyto-toxic in *in vitro* cell assays. Additionally, changing disinfectants equates to changing oxidants—and the switch to chloramines has been implicated in releasing lead from otherwise stable pipes in the nation’s capital and elsewhere. Thus, the cost-effective decision to use chloramines instead of to remove organic DBP precursors may have actually increased health risks for the public.

The number of unregulated DBPs in drinking water, and concerns about risks from N-DBPs, prompted my research group to focus on organic nitrogen in the late 1990s. We started by developing new pretreatment methods to accurately measure dissolved organic nitrogen (DON) in drinking water, and continued by focusing on compound classes that comprise DON. We found that free amino acids are a very small part of the DON pool, which brought into question our ability to translate model compound reactivity studies that were available at the time to predict N-DBP formation. Instead, macromolecular proteinaceous materials (hydrolysable amino acids) are more abundant in drinking water.

We also found that many anthropogenic compounds contain organic nitrogen in sources ranging from pharmaceuticals or personal care products to cationic polymers used in water treatment plants. We proved that organic bases and proteins may represent less than 10 percent of the dissolved organic carbon (DOC) in water, but may account for more than 80 percent of the DON. Unfortunately, current drinking water systems are ill-equipped to remove base fractions and, therefore, poorly remove reactive DON because they are designed to remove acidic fractions and hydrophobic DOC. The combined recognition that DON exists in drinking water, coupled with the increased use of chloramines, has probably resulted in more human exposures to N-DBPs in drinking water while attempting to decrease the regulated DBPs. Were these risks foreseeable when DBP regulations were tightened?

**Hammers to the Rescue**

As engineers address water problems such as waterborne pathogens and known DBPs, surely they can invent new technological tools—the “hammers”—to address new byproducts or corrosion issues. Crises of the past have shown this to be true. For example, ultraviolet (UV) light disinfection really emerged after a *cryptosporidium* outbreak in Milwaukee, and now UV technology is increasingly common in drinking water systems. But does our technology always improve human outcomes?

Consider a study we did in a small community of 3200 people in California that had arsenic in its groundwater supply. New arsenic regulations in 2001 required that a treatment system had to be placed on the wellhead. We considered three types of adsorbents to achieve compliance with the arsenic regulations, which are based upon a 1 in 10,000 avoided cancer risk. Thus, it is possible that no one in this community will actually be prevented from cancer caused by arsenic, but the community would continually pay for the installation and operation of the treatment system.

Then we applied lifecycle assessment tools—not to predict CO2 equivalents, as is commonly done in the water industry—but we focused on cancer potential associated with producing the adsorbents in either Houston, China, or Germany. The end result was that the burden of manufacturing the adsorbents and chemicals could actually result in exporting the cancer risk to other locations. To potentially avoid one cancer in the California community, health risks are transferred to workers and the public in communities that manufacture the treatment materials. Exporting cancer risk is an example of the geospatial impacts of our water treatment decisions.

Now we use lifecycle thinking to design new technologies (better hammers) through the National Science Foundation Engineering Research Center for Nanotechnology Enabled Water Treatment (NEWT). One of our goals is to minimize or reduce dependency on chemicals that lead to sludges and byproducts and limit the deployment of small, decentralized water treatment systems.

To treat drinking water, NEWT uses the unique properties of engineered nanomaterial, which can be excited by various parts of the electromagnetic spectrum from deep UV through microwave or radio frequency wavelengths, along with high and selective surface areas, electrical conductivity, magnetism, or tunable surface hydrophobicity. One of our inventions uses side-emitting optical fibers, and will deliver disinfecting UV‑C light from non-mercury-based light emitting diodes to disinfect water and prevent biofilms. By not using mercury-based LEDs, society can reduce exported risks.

Although it is easy to be distracted by the contaminant *du jour*—PFAS, for example—NEWT focuses on the science to treat both emerging and persistent human health challenges. For example, excessive nitrate is one of the top 10 most reported drinking water violations. Nitrate is the most commonly occurring anthropogenic pollutant in groundwater in the United States, Europe, and China, and is associated with agricultural fertilizer use. Too much nitrate in water has led many communities to abandon otherwise viable groundwater sources.

While the current drinking water regulation for nitrate is based on protecting infants from health risks (methemoglobin), new epidemiology studies show stronger correlations between nitrate and bladder cancer than THMs, which drove the regulated limits for THM. Nitrates are also now implicated in a number of cancers for some sensitive populations, and may be involved in endocrine disruption. Current nitrate treatment technologies separate nitrate in water rather than destroying it, are relatively cost prohibitive to use, and generate waste streams that pose other risks. NEWT is exploring a new class of technologies—advanced reduction processes (ARPs)—for chemicals like nitrate.

While the drinking water industry has many advanced oxidation process (AOP) alternatives, it lacks ARPs, which are needed for an increasing number of emerging pollutants. Focusing on nitrate allows us to develop new ARPs that will destroy nitrate using nanotechnology. Fundamental science discoveries that result from ARP research may lead to breakthrough technologies for other pollutants that require reduction technologies, such as chlorinated or fluorinated organics.

These examples show how engineers can develop new technological hammers to solve problems. In each case, we try to minimize unintended consequences using lifecycle assessment tools. However, the increasingly narrow focus of such technologies continues to put patches on the water system, rather than taking a more holistic approach that reduces human health risks instead of exporting them.

**Unintended Actions Create Water Crises**

Meeting regulations and meeting water *quantity* demands has emerged as the standard business model for consultants and municipalities—which is very different from the 1850s public health goals. Even through the early 1970s, the focus was on reducing human and ecosystem exposure to pollutants, not just meeting regulations for an outdated list of pollutants. Is the water industry missing important societal trends? Could this business model put past achievements, which extended life expectancy, at risk?

Today, from California to the Middle East, Singapore, or Cape Town, desalination technologies are being adopted to meet water demand by treating seawater, wastewater, or brackish groundwater. The global desalination market will surpass $27B by 2025. However, society is sending other, contradictory messages about water. The bottled drinking water market will exceed $300B by 2021, and the market for point-of-use water filtration devices already exceeds the desalination market. Consumers are saying that they either don’t trust or don’t like the aesthetics of tap water, which fundamentally underpins consumer confidence. We may argue these are marketing games, but these trends can and should not be ignored. The water industry must understand how to better meet consumer demand for water *quality*.

The drive to manage water quantity permeates many architectural and engineering domains. For example, LEED-certified green buildings are designed to conserve energy and water. While conservation is important, this trend creates unforeseen consequences. We (and others) are seeing that reduced water use in commercial buildings causes increased water age, loss of chlorine residuals, time-dependent redox conditions that lead to copper and lead corrosion in pipes, doubling of thihalomethanes (THMs) inside the buildings, and *legionella* risks. These were all foreseeable challenges, but who was looking out for this? While buildings manage air *quality and quantity* (for example, particles, temperature, humidity, ventilation rates), as LEED-certified buildings become increasingly tight, we only conserve water in buildings. To improve water quality in all buildings, stopping at the street where homes and buildings connect to the water supply is unrealistic if the goal is public safety rather than cost or convenience.

Many other societal drivers impact drinking water. In the past, we used to spray DDT in public swimming pools and water bodies to prevent the spread of diseases; clearly, this was a problem. Many of these legacy pollutants are still detectable. Now, society is making equally radical decisions that directly and indirectly affect water systems. The 1980s marketing phrase, “Better living through chemistry,” has been realized. The sale of prescription drugs has grown from $40B in 1990 to nearly $400B by 2020. Illegal drugs and illicit use of prescription drugs has also increased.

Clearly, preventing disease has improved quality of life and longevity. But it took years for the water community to develop analytical tools to detect these chemicals and pharmaceuticals in our drinking water supply. Wasn’t this, to some degree, foreseeable? What does their presence in drinking water mean? They are largely unregulated and the risks are likely low due to their low concentrations. But, are we sure?

Our team found that one pharmaceutical, methadone, which is prescribed for back pain and heroin addiction treatment, occurs in wastewater effluent and at drinking water intakes in concentrations that can produce a potentially carcinogenic DBP (NDMA) during chloramination. In other words, a drug meant to benefit some people may put millions of other people downstream at risk. Currently, pharmaceuticals are present in drinking waters. Based upon a number of arguments the water industry has largely decided not to implement treatment which can remove pharmaceuticals in drinking waters. This may come at risks down the road, or immediate risks from consumer confidence.

Monitoring every pharmaceutical or new chemical will be nearly impossible, and it may actually cost more to define the problem than to solve it. Our team has taken a different approach, one based upon geospatial models to identify areas for elevated risk. It is within higher risk communities that decisions could be considered. We developed a model called DRINCS (De facto Reuse In our Nations Consumable water Supplies) that includes the precise location of every municipal wastewater discharge into surface waters, along with all the data on the size and type of treatment at the wastewater treatment plant (WWTP); we link that to USGS streamflow models which permits us to estimate the percentage of water of wastewater origin at every drinking water treatment plant using surface water (SWTPs) across the United States. We find that more than 50 percent of these SWTPs have at least one upstream WWTP discharge, but the magnitude of de facto reuse (percentage of water of wastewater origin in a SWTP intake) is relatively low (less than 5 percent, on average). However, dramatic seasonal variations exist, especially on smaller river systems, and de facto reuse can frequently exceed 20 percent. This is not necessarily bad, because it shows the importance of renewable wastewater as a key part of our water supply—but it does affect water quality (for example, algae growth, pathogen loads, and pharmaceuticals).

DRINCS allows evaluation of national trends, but also deeper dives into understanding complex systems. For example, we find in Texas that smaller communities are both 1) at higher risk of exposure to wastewater derived pollutants because they have higher levels of de facto reuse, and 2) lack advanced technology capable of treating these types of chemicals. Based upon associated databases on water quality based health violations and statistics on income by zip codes or cancer reports by counties, we can start to understand reasons for inequities in water quality and potential adverse outcomes.

**A Big Data Path Forward**

DRINCS is just the beginning of the type of tools the water industry needs to understand impacts of societal drivers on water quality. Geological factors, agriculture, energy, and other industrial sectors can be integrated into such models. While DRINCS focuses on inputs/outputs of municipalities, there are massive improvements that can go beyond databases, and through machine learning and Monte Carlos simulations begin applying principles of artificial intelligence to find existing or future patterns in risk factors that lead to human health risks. Such models will help us identify the geospatial location of communities at highest risk, locations within communities (e.g., LEED certified buildings, buildings of certain ages, buildings with certain intended uses (e.g., hospitals, schools, health care facilities) where high-risk individuals spend their time, etc. Such locations should then become the focus of decentralized treatment systems that provide truly *safe* water to people and not just water that meets regulations that require decades to promulgate.

The water industry has been viewing artificial intelligence as a tool to optimize water treatment performance, leading to lower costs and more consistent water quality. These are important uses. However, many sectors of industry are embracing AI technologies in far broader applications. With relatively small investments, we can create water information technology system that aims not at reducing costs, but one with the national aim of improving drinking water quality – both as perceived by consumers and backed by science. Consider a virtual reality, not unlike the holodeck on *Star Trek Voyager*, that could be entered physically or through conversation where scenarios could be posed and analyzed at multiple spatial and temporal scales related to our water systems. Expert humans are good at identifying first- and even-second order effects of our decisions, but beyond that we lack the knowledge and skills to address higher order challenges. The presence of pharmaceutical prescriptions and potential formation of DBPs in drinking water falls within those first- or second-order analyses. But, how would a water expert approach predicting impacts on water systems from other broad societal trends (e.g., autonomous vehicles, gig-economy, etc.)? While such technology may be decades away, what is missing today is ownership of such a vision. Water is integrated into over 20 federal agencies, and thousands of other stakeholders across the nation. While creating a Federal Department of Water may be appealing, a more realistic path would be for the drinking water community itself to step forward and provide leadership on a truly integrated national water model that defies institutional boundaries, securely shares data, links complex and disparate databases and allows any stakeholder to contribute to and explore scenarios. Through such models we can avoid the whack-a-mole patching of problems with technology, identify where new technological “hammers” are really needed, and provide strategic foresight for solutions focused on predicting and improving well-being outcomes for ecosystems and people.

##### About the Clarke Prize

The Clarke Prize is named after Mrs. Athalie Richardson Irvine Clarke, a native Southern Californian who was active in both business and philanthropy. As co-founder of the National Water Research Institute (NWRI), Mrs. Clarke recognized the vital importance of clean water.