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How Safe Is Safe in the Treatment of Drinking Water for the Public?

R. RHODES TRUSSELL, PH.D., P.E., BCEE, NAE

Chairman and Chief Executive Officer

Trussell Technologies, Inc.

Pasadena, California USA



Today, the public is asking important questions about the safety of our drinking water, particularly with respect to the increasing presence of manmade chemicals. Regulators, environmental scientists, and the drinking water industry have been studying and debating this issue for several decades now. Significant investment has been made, yet questions remain.

This paper attempts to put the problem in perspective relative to both the growth of human commerce and the development of our scientific understanding. The focus is on questions of human health and drinking water in the decades ahead, keeping in mind the recent interest in potable reuse. In structuring the discussion, an attempt has been made to maintain a long-term perspective, both forward and backward in time.

Early Focus on Microbial Disease

The connection between drinking water and health was first made in 1854 by John Snow, a noted physician in Victorian England. Using

maps and interviews of the affected population, Snow demonstrated the connection between cholera in the area of Golden Square in London and drinking water from the Broad Street well (Hempel, 2006). In so doing, he created a new mission for those serving drinking water to the public and fathered the modern science of Epidemiology.

Following Snow's demonstration, the ability of drinking water to serve as a conduit for the transmission of waterborne disease became a focal point for the public health community. As a result, during the late Nineteenth Century and the first six decades of the Twentieth Century, investments in the treatment of drinking water were largely focused on the prevention of waterborne disease. Cholera, typhoid fever, and dysentery were nearly eliminated (Crittenden et al., 2012). Filtration and disinfection were the keys to success – especially disinfection, which came online much more quickly (McGuire, 2013). Data on death rates in the U.S. throughout the Twentieth Century, displayed in Figure 1, demonstrate that the water industry's efforts in filtration and

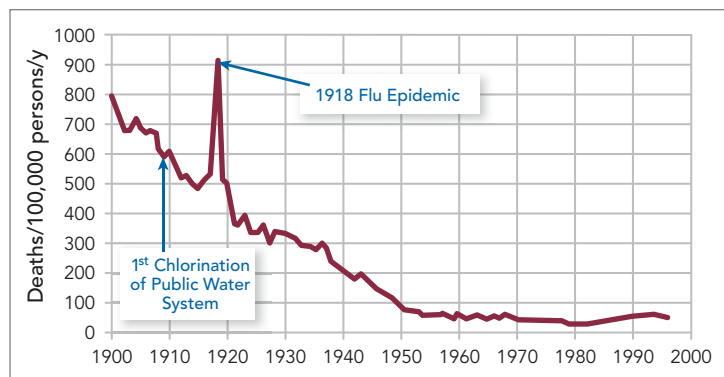


Figure 1: Death rate in the United States in the first six decades of the Twentieth Century (adapted from CDC, 1999).

disinfection had huge benefits. In fact, by the end of World War II, *drinking water safe from microbial disease had become the hallmark of civilization*. It was one of the miracles of the first half of the Twentieth Century (CDC, 1999).

The Chemistry Miracle and Its Dark Side

Safe drinking water was only one of the miracles of science and engineering in the Twentieth Century. Another miracle was that of “better living through chemistry.”¹ Synthetic rubber, nylon, dichlorodiphenyltrichloroethane (DDT), and penicillin were all discovered in the 1930s, and citizens of the 1940s and 1950s marveled at the benefits of these chemical innovations. The highly selective herbicides invented in the 1950s provide a good illustration of the milieu of the time. Before 1956, raising a dichondra lawn meant that the homeowner invested significant time and work every season weeding out invasive Bermuda grass. After 1956, one could spray a dichondra lawn with Dowpon (dalapan) and kill the Bermuda grass without touching the dichondra itself, which was truly amazing. The power of our man-made chemicals seemed unlimited – to the layman, almost magical.

Then, in 1962, Rachel Carson wrote *Silent Spring* (Carson, 1962), a book in which she demonstrated that some of the most miraculous manmade chemicals (e.g., dieldrin, toxaphene, heptachlor, and DDT) had significant unanticipated consequences. Carson not only gained

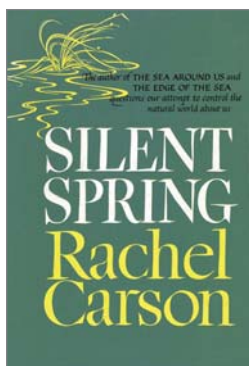
the attention of President John F. Kennedy who, upon reading her book, directed his Science Advisory Committee to investigate, but she also sent a message that resonated throughout the worldwide scientific community: Manmade chemicals, particularly organic chemicals, may have consequences beyond which they were originally intended, and those consequences may not be good. Carson’s most dramatic demonstration, the effect of DDT on egg formation in birds of prey, was evidence of interference with the function of the endocrine system. Cancer has long been associated with chronic exposure to certain substances (Pott, 1775), and this connection was demonstrated in a scientific manner in the second decade of the Twentieth Century (Yamagiwa and Ichikawa, 1918). Cancer is a mysterious, devastating disease; it is not surprising that much of the subsequent concern about manmade chemicals in drinking water has been focused on possible carcinogenic effects.

Analytical Science Brings Trace Organics to Drinking Water

Before *Silent Spring* was published, the U.S. Public Health Service had already expressed concern about manmade organics in water supplies, particularly with respect to problems associated with taste and odor, but also because of potential toxicity.

In the 1950s and 1960s, analytical methods were limited; therefore, the U.S. Public Health Service developed a gravimetric method that used carbon adsorption and chloroform extraction to estimate the amount of organic material present. The method filtered 5,000 gallons of water over a 2-week period (Middleton et al., 1952). Shortly after the publication of *Silent Spring*, the U.S. Public Health Service published evidence that their carbon chloroform extract could be carcinogenic (Heuper and Payne, 1963), and set out to develop a more convenient version of their gravimetric technique. The technique, which they published 10 years later, passed 60 liters (L) of water through a column containing 60 grams (g) of granular activated carbon (GAC) over a 48-hour (h) period. The column was then extracted first with chloroform and subsequently with 95-percent ethyl alcohol,

¹Trademark used by DuPont.™



evaporating the extract to determine the mass of the material adsorbed. This process took 10 days to produce a sample (Buelow et al., 1973), and the method – called the carbon chloroform extract (CCE) – did not give satisfactory results.

In the meantime, analytical techniques improved, particularly with the commercialization of the gas chromatograph-mass spectro-

meter (GC-MS) by EAI/Hewlett Packard and the Finnegan Instrument Corporation. In 1974, using this technology, a U.S. Environmental Protection Agency (USEPA) team led by Jim Symons and Al Stevens, both formerly with the U.S. Public Health Service, conducted a National Organics Reconnaissance Survey (NORS) of U.S. drinking waters (Symons et al., 1975). Evidence of organic chemicals in surface water supplies exposed to industry was identified in that survey (Trussell and Trussell, 1980), which helped stimulate the 1974 Safe Drinking Water Act. Soon after, the USEPA conducted the National Organic Monitoring Survey, which focused on data requirements for the regulatory process itself (USEPA, 1977; Brass et al., 1977).

The 129 Priority Pollutants

Toxic chemicals also became an issue in the management of wastewaters, particularly industrial wastewater. Prior to 1976, efforts with the Clean Water Act focused on regulating the discharge of conventional pollutants, such as biological oxygen demand (BOD) and suspended solids. Limits were set on a case-by-case basis, determined by the assimilative capacity of the receiving waters. “Toxic chemicals” were not given special attention.

The Natural Resources Defense Council (NRDC) and other environmental groups concerned with toxic organics were dissatisfied with the USEPA’s approach and sued. In June 1976, a consent decree between the parties was reached (NRDC vs. Train, 1976). This consent decree reorganized the USEPA’s view of toxic chemicals. Congress incorporated most of the details of the consent decree into 1977 amendments to the Clean Water Act (P.L.95-217).

The consent decree became known as the “Toxics Consent Decree,” or the “Flannery Decision” (named after presiding Judge Thomas A. Flannery). It required the USEPA to regulate a specific list of 65 chemicals and “classes of chemicals.” The 65 were subsequently divided into 129 distinct compounds, which have since been referred to as “the priority pollutants” or “129 Priority Pollutants.”

Thus, a major change in the administration of the Clean Water Act as of 1977 was the specification of different standards for toxic and conventional pollutants – a distinction not made in earlier regulatory practice. Because municipal wastewater treatment plants were designed to treat domestic and industrial wastewater, the USEPA established the National Pretreatment Program in 1973, requiring industrial and commercial dischargers to control pollutants in their discharge to municipal systems. Under this program, wastewater authorities adopt ordinances, issue permits, monitor compliance, and take enforcement action. Where municipal wastewaters are concerned, this pretreatment program has become the primary vehicle for regulating toxic chemicals.

A summary of the pretreatment program’s achievements demonstrates significant reductions in the discharge of toxic chemicals (USEPA, 2003). But the list of the “129 priority pollutants” has not changed since the inception of the program and does not reflect an up-to-date assessment of the toxic chemicals used in industry today (NRC, 2012). A few years ago, an update was proposed in the form of a Universal Wastes Rule that would incorporate a variety of wastes, including pharmaceuticals, and reduce the amount of these chemicals in wastewater (73 Fed. Reg. 73520, Dec. 2, 2008). When published, the final act fell short of its original scope, narrowing the focus to pesticides, mercury, and the wastes from batteries and light bulbs (USEPA, 2012). The recent National Research Council (NRC) Committee on Reuse suggested that, “Updates to the National Pretreatment Program’s list of priority pollutants would help ensure that water reuse facilities and *de facto* reuse operations are protected from potentially hazardous contaminants.” As the NRC uses the term, “*de facto* reuse” refers to a drinking water supply that contains a

significant fraction of wastewater effluent, although the water supply has not been permitted as a water reuse project (NRC, 2012).

Disinfection Byproducts

Members of the USEPA NORS team, including Tom Bellar, Jim Lichtenberg, and Robert Kroner, used a new purge-and-trap technique and a gas chromatograph with a Hall Detector (which is especially sensitive to halogens) to identify four trihalomethanes (chloroform, dichlorobromomethane, bromodichloromethane, and bromoform) that were observed to appear following chlorination (Bellar et al., 1974). Meanwhile, that same year, Dutch chemist Johannes Rook – using a headspace technique borrowed from the beverage industry and gas chromatography with a flame ionization detector – made the same finding at the Berenplaat, one of the largest water treatment plants in Europe (Rook, 1974). These were truly revolutionary findings, and they began a struggle that is still underway four decades later – namely, the effort to find ways to protect and even extend the benefits of drinking water disinfection (one of the cornerstones of modern civilization) without forming undesirable chemical byproducts that could jeopardize those benefits.

For approximately one decade, the focus remained on trihalomethanes (THMs), particularly chloroform. However, it was clear from the beginning that the reaction between chlorine and natural organic matter in drinking water formed a large number of organic compounds, THMs being only a small fraction of the whole (Christman et al., 1983). Today, that work continues, and we are completing the third round of drinking water regulations on disinfection byproducts (DBPs) (USEPA, 1979, 1980, 1998, 2006). It seems unlikely that the water industry has seen the end of this struggle. The issue is important because it has placed a constraint on the development of alternatives for disinfecting water, gradually driving the industry away from simple chlorination, the principle chemical responsible for the revolutionary improvement in health observed in the first half of the Twentieth Century.

VOCs in Groundwater

The same improvements in analytical technique that enabled the identification of THMs soon revealed other trace organic contaminants in drinking water withdrawn from underground aquifers. The discovery of volatile organic chemical (VOC) solvents in deep, protected groundwater supplies in California (which occurred in the late 1970s) and similar findings throughout the nation helped stimulate action. The USEPA's Office of Water promulgated a regulation on VOCs in 1986 (USEPA, 1982). Compounds addressed in this first regulation were trichloroethylene, carbon tetrachloride, 1,2-dichloroethane, vinyl chloride, benzene, 1,1-dichloroethylene, and tetrachloroethylene.

The VOC findings also gave new momentum to existing efforts under the Resource Conservation and Recovery Act (RCRA), and helped stimulate the 1986 Superfund Revenue Act (CERCLA), as well as the 1986 RCRA amendments. Over the next decade, these became the foundation for the nation's largest environmental program, much of which has been focused on protecting groundwater supplies. Meanwhile, additional synthetic compounds were found in groundwater. Some examples include dichlorobromopropane (DCBP), N-nitrosodimethylamine (NDMA), methyl tertiary butyl ether (MTBE), and perchlorate. All but perchlorate are organic.

Leaching of Contaminants into Drinking Water

In the late 1970s, concerns developed about contaminants leaching into drinking water through (or from) the facilities used to deliver water, both in the utility's system and in consumer plumbing. These concerns can be divided into four groups:

- Contaminants in water treatment chemicals.
- Contaminants (particularly gasoline and chemical solvents) leaching from the environment through plastic pipe and into drinking water (Thompson and Jenkins, 1985; Selleck and Mariñas, 1991).
- Contaminants like chemical solvents leaching from coatings used to protect the surface of water facilities.
- Metals like lead and copper leaching from water conduits themselves.

Ultimately, all impacted water treatment strategies or the materials used in water systems.

Potential contaminants in water treatment chemicals became a concern when carbon tetrachloride was found as a contaminant in chlorine. The USEPA funded an NRC expert panel led by Bill Glaze to investigate the matter, and the interim outcome was a Drinking Water Chemicals Codex (NRC, 1982) modeled after the Food Chemicals Codex that was published by NRC and funded by the U.S. Food and Drug Administration (FDA). At the same time, a number of contaminants, particularly VOCs, were found to leach from linings and coatings used by the industry. The USEPA asked NRC to reconvene the Glaze Committee to provide guidance on a third-party process for certifying drinking water chemicals and drinking water system components. The net result was a process that established National Science Foundation (NSF) Standards 60 (water treatment chemicals) and 61 (drinking water system components).

The Decision to Act

When DBPs were found in drinking waters throughout the nation and when VOCs were identified in several important groundwater basins, drinking water regulators and the drinking water industry faced some difficult decisions.

On one hand, these compounds were generally found at very low levels – so low they had not been detected previously. Also, the evidence that they represented a health risk was second-order science in the sense that there was no direct evidence of health consequences from human exposure. Rather, the only evidence came from studies with animals exposed to much higher levels of the compounds. In spite of the potential for misunderstood effects in these types of studies, evidence was being extrapolated across species, across several orders of magnitude in concentration, and across several decades of exposure (Tardiff, 1977). It would be a long time before the issue would be settled science. Finally, with all this uncertainty, the risks imputed were generally small when compared to the risks that the population ordinarily engages in during the everyday decisions of life.

Even though there was ambiguity about risks, where the consumer is concerned, the risks are involuntary – and some were concerned about the matter. Important figures in the water industry began to advocate that, “In light of the long period of uncertainty ahead, where the significance of these contaminants would not be understood, the prudent thing would be to remove them.” Abel Wolman, a highly articulate and trusted advisor, was among the most visible of these figures (Wolman, 1986).

It could be said that the black-and-white outlook reflected in the “Delaney Clause” represented the view of both Congress and the environmental community at the time (Merrill, 1997). The Delaney Clause, repealed in the mid-1990s, said, “The Secretary of the Food and Drug Administration shall not approve for use in food any chemical additive found to induce cancer in man or, after tests, found to induce cancer in animals.”

Operating in that environment, the USEPA’s Office of Water proposed a regulatory structure with maximum contaminant level goals (MCLG) of zero for all carcinogens and proposed to set the maximum contaminant limits (MCL) for most of them at the “Practical Quantification Limit,” arguing they could not be set lower given current analytical technology (USEPA, 1982). Internally, the USEPA ultimately adopted a policy of managing in a risk window between 10^{-4} and 10^{-6} excess cancers per person per lifetime. Where possible, risks would be regulated to within this window, and further regulation would not be pursued for risks beneath the window. As of 1982, regulations put the VOCs beneath this window, but DBPs were thought to be within the window, meriting further regulatory development as improvements in technology permit.

Fundamentally, however, with the exception of DBPs, the regulatory infrastructure was one of maintaining these toxic compounds below the limit of detection – that is, to be in a position to say that they must be removed. There is an active debate today as to whether regulations in potable reuse should take the same direction.

Chemicals of Emerging Concern

In the 1990s, concern began to develop that certain manmade substances might play a special role in the environment. In simple form, the idea is that some manmade chemicals may mimic natural hormones – binding with endocrine receptors in a way that produces unnatural outcomes. This hypothesis has its roots in certain molecules known to mimic the behavior of natural hormones. At the Wingspread Conference in 1991, the term “endocrine disrupter” was coined for these hormonally active substances. As pointed out by the NAS (NRC, 1999a), the issue can be viewed as a question of the possible influence of any hormonally active agent. Such agents might mimic hormones, interfere with the ability of hormones to carry out normal function, degrade hormones, interfere with the body’s ability to synthesize hormones, influence the ability of hormones to enter a target cell, and so on. All these activities would fall under the purview of current concerns of those who discuss endocrine disrupters.

Perhaps the most easily understood examples occur in the reproductive system. For example, the synthetic compound ethinyl estradiol (17 α -ethinyl estradiol) is used in birth control pills to mimic the behavior of natural estrogen (17 β -estradiol). One of the most widely recognized endocrine disrupters, Diethylstilbestrol (DES), also affects the reproductive system. DES was widely used as hormone therapy for pregnant women in the 1950s and 1960s. It is now known to result in serious abnormalities in children, and the use of DES has been banned since 1971.

Also in the 1990s, several studies reported hormonally active agents in specific environments. For example, pesticides were associated with the decline of American alligators in Florida (Gliette et al., 1994). The feminization of fish was documented downstream of sewage discharges (Purdom et al., 1994; Jobling et al., 1995, 1998). Several classes of chemicals have now been implicated. These include synthetic steroids, pesticides and herbicides, phthalates, alkylphenol ethoxylate surfactants (Soto et al., 1991), dioxins (Bishop et al., 1991), and polychlorinated biphenyls (PCBs) (Bitman and Cecil, 1970), as well as natural chemicals like natural estrogen and the phytoestrogens

found in many plants, including the soybean (NRC, 1999a). So far, all the unambiguous evidence for effects is in connection with ecosystems, and not with exposure to humans.

Just before the start of the Twenty-First Century, available analytical data were only sensitive enough to document the presence of these contaminants and those like them at limited locations as part of special efforts in research. *But analytical chemistry has been one of the most rapidly advancing sectors in water science* and, as techniques continue to improve, surveys with these new techniques began to demonstrate that a variety of compounds could be found in all municipal wastewaters and in most surface waters at very low levels. Thomas Heberer at the Technical University of Berlin and Thomas Ternes at a water utility in Weisbaden, Germany, first reported the presence of large numbers of pharmaceuticals in European rivers and streams (Heberer et al., 1997; Ternes, 1998). Then, in 2002, Dana Kolpin of the U.S. Geological Survey published the results of a national reconnaissance survey showing that these same compounds were widespread in U.S. waterways as well (Kolpin et al., 2002).

Subsequent industry-sponsored surveys conducted by the research lab at the Southern Nevada Water Authority showed that many of these compounds were also common in U.S. drinking water supplies (Benotti et al., 2008). These compounds include:

- Residuals of drugs that the population takes to protect its health and then passes into the environment through urine.
- Residuals of personal care products like perfume, insect repellent, or sunscreen.
- Natural hormones like estradiol or synthetic hormones like ethinyl estradiol, which are used for birth control.
- Sweeteners used to reduce our sugar intake, like sucralose or acesulfame K.

Some of the most persistent of these compounds have also been found in drinking water (Benotti et al., 2008).

Now water quality managers have a new concern. These emerging contaminants occur at the part-per-trillion level, almost a thousand-fold lower than the DBPs and VOCs encountered by the industry four

decades ago. Again, the levels and effects are low enough that it is hard to know the best course of action. Moreover, as the industry works to meet this challenge, it is becoming clear that resolving it will require the resources of not only the drinking water industry, but also the wastewater industry and the companies that produce the chemicals in the first place. A new consensus must be achieved regarding *what* it means to have “safe” water.

The CEC Dilemma Is a Harbinger of a New Era

The time has come to recognize that these trace organics, which have become increasingly common in today’s environment, are harbingers of a new era – an era that the Earth entered about six decades ago, *an era where the scale of human activity is so vast that no part of our Mother Earth can escape its impact*. As the human population continues to increase, as the level of commerce increases with that population (indeed, faster than the population increases) (Figure 2), the detritus of our civilization will become increasingly present in the environment around us.

Trace organic chemicals in our drinking water are not the only form this detritus takes. The smog in Los Angeles, Mumbai, and Beijing is another example. Acid rain in North America and Europe is another. The hole in the ozone layer and global warming are also examples. Where drinking water is concerned, it is the accumulation of these trace organic chemicals in our water that has become an issue we must confront.

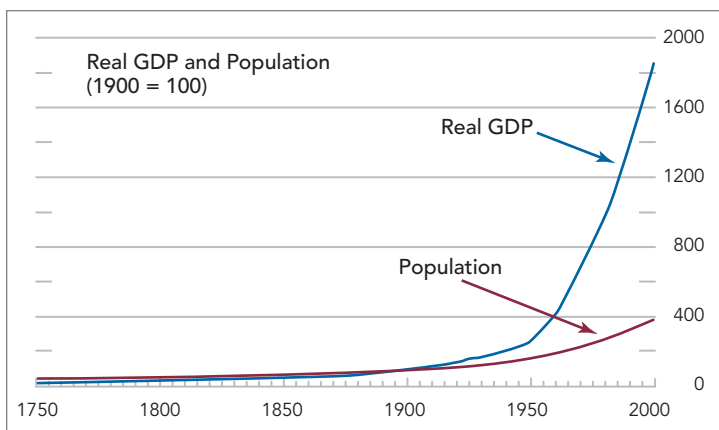


Figure 2: Comparison of the growth of the world’s population and Gross Domestic Product (IMF, 2000).

The longstanding position of public policy has been to seek drinking water sources in their natural states (that is, water in which no manmade chemicals can be found). In this new era, however, finding water free of manmade chemicals is an elusive goal. The residuals of civilization are everywhere, and the ability of our best water chemists to detect, measure, and demonstrate it to us is on the increase. When faced with knowledge of the presence of even trace organics in our water supply, we generally expect our water managers to provide enough treatment to remove them. Technically, removing these organics means that the water quality manager must take their concentration below the limit of detection. Conveniently, if the manager has the water analyzed, he is in a position to say he found nothing.

But experience tells us that this approach to the problem is not sustainable. As the science of water analysis continues to improve at a rapid pace, water chemists are able to find the chemical detritus of civilization at lower and lower levels. A case can be made that, since 1970, analytical technology has been one of the fastest growing areas of water science. A crude plot of the history of detection limits for measuring trace organics in water over the last 5 decades is shown in Figure 3. In the figure, that same rate of improvement is projected forward to the end of the new century. In 1960, we were using packed columns with flame ionization detectors for a few pesticides. The detection limit was little better than 1 milligram per liter (mg/L) (Harley and Pretorius, 1958). By the mid-1970s, we were at about 10 micrograms per liter (µg/L) using purge-and-trap and GC-MS. By the mid-1980s, we were pushing 1 µg/L using capillary GC-MS. Today, our analytical chemists are pushing below 1 nanogram per liter (ng/L) with liquid chromatography-tandem mass spectrometry (LC-MS/MS). At that same rate, we will be at 1 picogram per liter (pg/L) by 2035, and 1 molecule per liter at the end of this century.



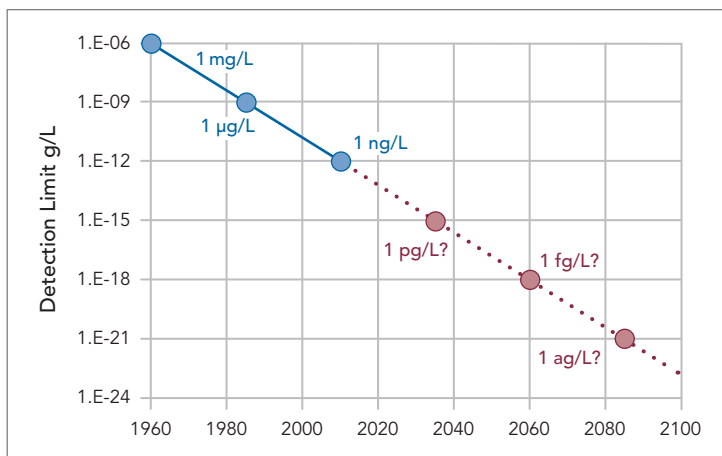


Figure 3: Detection limits are rapidly dropping (author's approximation).

These detection limits seem to be improving at a rate much like the technology developed in Silicon Valley, as described in Moore's Law (Moore, 1965). Moore's idea was that the number of transistors on a microchip doubles every 18 months. A similar law for the analysis of organic chemicals would be that the detection limit for trace organics drops by three orders of magnitude every 25 years.

What does it mean? There is another important insight here. Increasingly, our chemists can show something is in the water, but the rest of science cannot tell us what its being there, at that level, means. Surely there is a point beyond which its being there, at that level, means nothing. Therefore, the question we must answer is, "When is the water safe?"

Discussions of Risk

The present decision-making structure in the U.S. is based on understanding the risks associated with different environmental threats. It has its roots in a 1983 report by the National Academies that developed a four-part framework (consisting of hazard identification, dose-response assessment, exposure assessment, and risk characterization) and published it in what is known as the "Red Book" (NRC, 1983). Since then, it has been developed further through contributions from the NRC, USEPA Science Advisory Board (SAB), and others. Notable among these efforts was a 1987 USEPA report on the relative risks associated with different environmental problems (USEPA, 1987)

and a 1990 report by the USEPA SAB recommending that relative risk be used as a tool for allocating resources (USEPA, 1990). The NRC updated their report in 2009, introducing several new elements to the process in the areas of problem formulation, stakeholder involvement, and results evaluation, noting that risk management decisions should not just consider risk, but also issues of economics, equity, and law (NRC, 2009).

The NRC's recommendations for the USEPA's Contaminant Candidate List (CCL), as shown in Figure 4, were also an effort to make the process of contaminant identification more comprehensive while at the same time streamlining it (NRC 1999a, 1999b, 1999c, and 2001). The idea was to periodically review a broad list of contemporary compounds and then narrow the field by using an approach that focuses on compounds that show occurrence or the potential to occur in drinking water and demonstrate adverse health effects or the potential to cause adverse health effects. The result would be a much more abbreviated "pre-CCL," which would be carefully scrutinized. Compounds still found to be of interest after a more detailed examination would be formally placed on the CCL list, a process that would require the USEPA to study the compound's occurrence and toxicity and make a regulatory decision. In the end, however, this process has proven slow as well.

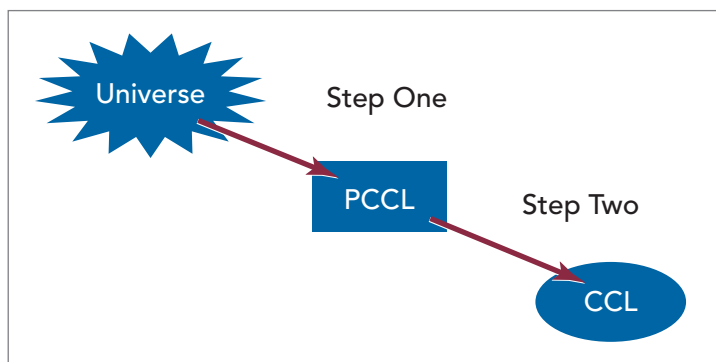


Figure 4: The CCL process proposed by the NRC (NRC, 1999b).

These and related works have been instrumental in improving our understanding of environmental challenges and have helped to move the allocation of resources out of the political arena. Nevertheless, as the discovery process moves forward, the list of potential compounds

to be assessed is vastly outstripping the resources available for using formal risk analysis to allocate remedial resources and promulgate regulations. Also, the time we need to respond with corrective action is much too long. As a result, we find ourselves with an increasingly long list of unregulated compounds of unknown significance. At present, adequate guidance is not available to help the public gain perspective on this unregulated community of chemicals.

The New Era Calls for a Hybrid of the Precautionary Approach

In Europe, the Precautionary Principle has been advanced as an alternative means for dealing with these problems. In concept, the Precautionary Principle is "...a general rule of public policy action to be used in situations of potentially serious or irreversible threats to health or the environment, where there is a need to act to reduce potential hazards before there is strong proof of harm" (Harremoës et al., 2001). The principle was first advanced in connection with the Montreal Protocol on substances that deplete the ozone layer in 1987, and was captured in the Rio Declaration on Environment and Development in 1992. It is obvious that the Precautionary Principle, implemented in a simple way, could quickly deplete resources to solve problems that may not ultimately prove important. As a result, careful choices will have to be made in its implementation. There are, perhaps, four principles that environmental engineers might adopt as guidelines for this new era:

Four guidelines for the new era include:

1. We should generally agree that we prefer not to have these manmade chemicals in our environment or drinking water.
2. We should recognize that this first principle is not universally achievable; therefore, we need a screen to help make intelligent investments and decisions before settled science is available.
3. In the treatment of both drinking water and wastewater, we should seek continuous improvement, implementing affordable broad-spectrum treatment technologies as they become available.
4. We should find substitutes for manmade compounds that persist

through our treatment processes and in the water environment, giving priority to those with adverse effects.

Screening Manmade Chemicals for Drinking Water

Of the four guidelines, the second – developing a screening process for toxics – is arguably the most important and most difficult to achieve. The need for a screen that can be used before settled science is available, however, leads to an essential question: Does the dialogue in the drinking water community need a new, more robust discussion on the questions of risk and when water is safe? As a society, when we gather scientific data about what our collective risks are, we reach agreement easily.

For example, data from the Centers for Disease Control and Prevention (CDC) (CDC, 2012) show a U.S. citizen's risk of dying from heart disease is about 24 percent, and the risk of dying from cancer is about the same (23 percent). But when we have a community or national discussion about the appropriate level of risk to which each citizen should be exposed as a result of a public service, such as the provision of drinking water, consensus is much harder to find. So far, where both environmental risk and risks associated with drinking water are concerned, our industry generally tries to engage the public in a discussion about the risk on the outcome side of a proposed project, attempting to find what risk is acceptable. The problem is one of communication.

When an engineer or scientist seeks to understand the safety of alternative outcomes, he or she normally begins by estimating the level of risk. For the layman, however, seeking safety is about avoiding risk altogether. Better bridges must be built between the scientist's understanding of risk and the layman's understanding of safety. That bridge might be the concept of *de minimis* risk. The term comes from the Latin "*de minimis non curat lex*," or "the law does not concern itself with trifles." A *de minimis* risk, then, is a risk that is too small to be concerned with. Someone exposed to that risk is considered "virtually safe."

While most agree on the *de minimis* principle, there are often

strong disagreements in specific circumstances as to what level of risk is, in fact, *de minimis*. For the public to accept the decision, the specifics cannot be resolved by science alone and are usually decided by an accepted authority, a regulator, court of law, or organizations like the National Academies.

Regulators already use a variety of criteria in managing risk for public enterprise, such as nuclear power, manufactured food, regulated pesticides, and drinking water (Rachman, 1990). Where there is special public interest (nuclear power), the public dialogue has pushed the *de minimis* level as low as a 10^{-6} lifetime risk on occasion, but generally 10^{-6} is used as a *de minimis* level. This puts the risk of exposure from these sources well beneath (several orders beneath) conventional risks in the household, like falling from a ladder. Generally, regulators seek to achieve *de minimis* levels when writing regulations; however, because regulations must balance risks and benefits, some regulations reflect a higher risk. Notable are regulations from the Occupational Safety and Health Administration (OSHA), which achieve a risk of 10^{-3} to 10^{-4} in the workplace, and the earlier regulations for DBPs in drinking water, which brought the risk beneath 10^{-4} .

As an example, USEPA's Office of Pesticide Programs generally treats a lifetime risk of one in a million as *de minimis* in regulating pesticides (Kamrin, 1997), and USEPA's Office of Water generally uses a window of 10^{-4} to 10^{-6} for regulation, treating risks below 10^{-6} as negligible. Generally, the FDA also treats a lifetime risk of 10^{-6} as *de minimis*, although some of its decisions also correspond to risks as high as 10^{-4} for naturally occurring compounds like aflatoxin (Rachman, 1990). Most regulatory agencies use a *de minimis* risk level of 10^{-6} or more.

Over the past six decades, the developed world has built a sophisticated infrastructure for considering *de minimis* risk for chemicals. These are reflected in guidelines, advisories, regulations, and other procedures regarding human exposure to chemicals in medicine, agriculture, food, and water, and are issued by recognized authorities like the USEPA, World Health Organization (WHO), FDA, California's Office of Environmental Health Hazard Assessment (OEHHA), and the National Institutes of Health (NIH).

Table 1 summarizes six compilations of *de minimis* benchmarks offered by reliable sources that have looked at drinking water. Methods for using these benchmarks to develop criteria for drinking water are outlined in the recent *Direct Potable Reuse State-of-the-Science Report* from the WateReuse Research Foundation (Trussell et al., 2013).

Table 1: Summary of Six Sources of *De Minimis* Risk Criteria Applicable for Drinking Water

Benchmark	Symbol	Units	Agency Sponsor
Reference dose	RfD	mg/kg/d	USEPA IRIS
Minimal risk levels	MRL	mg/kg/d	ASTDR
Acceptable daily intake	ADI	mg/kg/d	WHO
Acceptable daily dose	ADD	mg/kg/d	CA OEHHA
Long-term health advisory	HA	mg/L	USEPA
Predicted no-effect concentration	PNEC	mg/L	USEPA

mg/kg/d = Milligrams per kilogram per day

mg/L = Milligrams per liter

USEPA IRIS = USEPA's Integrated Risk Information System

ASTDR = Agency for Toxic Substances and Disease Registry

It seems reasonable that other guidelines regarding human exposure to chemicals in medicine, agriculture, and food might serve as a point of departure for estimating *de minimis* risk (Bull et al., 2011; NRC, 2012). Guidelines that might be considered include medical benchmarks for drug tolerance in humans, such as maximum recommended daily dose (MRDD), maximum recommended therapeutic dose (MRTD), and minimum oral therapeutic dose (MinTD), all of which were established by the FDA, as well as the maximum tolerated dose (MTD), which was established by NIH. A review of the issues by a recent National Water Research Institute expert panel suggests that the approach and criteria necessary for effective use of most of these benchmarks require further development (Crook et al., 2013).

Several studies have been undertaken, using the benchmarks discussed above (as well as others), to estimate *de minimis* levels for

emerging chemicals. A partial listing is provided in Table 2 of those studies that summarized results for a large number of chemicals. The Australian Guidelines and a recently completed study for the California State Water Board on CECs are notable for the long list of compounds evaluated, and the last two studies are notable for their examination of medical benchmarks.

The industry would be in a much stronger position to discuss the significance of the many non-regulated chemicals in the environment if a recognized independent authority made available a fairly comprehensive list of *de minimis* levels that could be used in the discussion. Moreover, it is important that the protocols used in establishing these *de minimis* levels be available for examination, making the process as transparent as possible. Through the work of existing organizations, notably the USEPA, many of these protocols are already available, but some further development would be required, particularly for the benchmarks in the medical and pharmaceutical industries.

Examining Pathogens and Anthropogenic Chemicals as “Chemicals of Concern”

Because the drinking water miracle of the first half of the Twentieth Century was so effective in controlling epidemic gastroenteritis and because our understanding of the role of anthropogenic chemicals in human health is far from complete, the contemporary community spends more energy and resources on the latter. However, increasing water scarcity will play a significant role in this new era. Our traditional strategy has been and will continue to be the call to conserve water. Another important strategy will be the reuse of water from our communities.

Increasingly, cost is driving us toward potable reuse. But what about those microbiological contaminants we started with when we began our efforts in water treatment? How important will they be in

Table 2: *De Minimis* Benchmarks from Secondary Sources

Benchmark	Symbol	Units	Agency Sponsor
Australian Drinking Water Guidelines	DWG	ng/L	NHMRC (2004)
Lowest Guideline Value	LGV	ng/L	Cotruvo et al. (2010)
Lower 95-percent confidence limit on the dose to induce tumors in 10-percent of animals	LTD ₁₀	ng/L	Gold (2007)
Provisional Guideline Value	PGV	mg/L	Schriks et al. (2010)
Monitoring Trigger Level	MTL	mg/L	Anderson et al. (2010)
Drinking Water Equivalent Level (Therapeutic Dose)	DWEL _{TD}	mg/L	Bull et al. (2011)
Pharmaceutical ADI	ADI _{ph}	mg/kg/d	Schwab et al. (2005)

the enterprise? One might ask, “Are there still pathogens that cause gastroenteritis in the used water from our communities?” The answer is a resounding “yes.” That is because there are still plenty of people around with gastrointestinal disease. True, the largest epidemics in history have all been associated with contaminated drinking water, but these pathogens also spread from person to person in daycare centers and, most notably, through our food.

As shown in Table 3, more than 26-million cases of gastroenteritis occur in the U.S. each year. That equates to about one case for every 12 persons per year. The organisms that make us sick are also the ones that we are likely to find in the feces of infected people and, therefore, in our sewage. The presence of these organisms in our used water is nearly inevitable.

It can be argued that these pathogens are chemicals that have evolved over the eons so that they have unique properties that can do us harm. Let us go through the exercise of characterizing one of these organisms as a “trace organic compound designed by Mother Nature,” and compare its health effects with one of the trace organics we are concerned about as a result of the growth of techno-science and the

Table 3: Fifteen Pathogens Causing the Highest Level of Illness in the United States Annually (After Scallan et al., 2011)

No.	Pathogen	Episodes	Hospitalizations	Deaths
1	<i>Norovirus</i>	20,796,079	55,825	569
2	<i>Giardia intestinalis</i>	1,121,864	3,289	31
3	<i>Salmonella</i> spp. (non-typhoid)	1,095,079	20,608	403
4	<i>Campylobacter</i> spp.	1,058,387	10,599	95
5	<i>Clostridium perfringens</i>	966,120	438	26
6	<i>Cryptosporidium</i> spp.	678,828	2,438	42
7	<i>Shigella</i> spp.	421,048	4,672	32
8	<i>Staphylococcus aureus</i>	241,188	1,063	6
9	<i>Toxoplasma gondii</i>	173,415	8,859	654
10	STEC non-O157	138,063	331	0
11	<i>Yersinia enterocolitica</i>	108,490	592	32
12	STEC O157	93,094	3,152	30
13	<i>Bacillus cereus</i>	63,411	20	0
14	<i>Vibrio parahaemolyticus</i>	40,309	116	4
15	Diarrheagenic <i>E. coli</i> other than STEC and ETEC	39,739	26	0

Note: The CDC compiled these data as part of a foodborne illness study; estimates were possible for 31 pathogens. Three additional viral pathogens (astrovirus, rotavirus, and sapovirus) were measured, but not included in this table due to the CDC's assumption that they are only relevant for children under 5 years of age.

new organic compounds that are proliferating in our water environment. Such a comparison is attempted in Table 4.

The trace organic chosen is NDMA (*N*-nitrosodimethylamine), which is on USEPA's current Contaminant Candidate List, the CCL3 (USEPA, 2009). The USEPA's current health advisory level for NDMA is 0.7 ng/L (USEPA, 2003). More recently, California's OEHHA (using more up-to-date protocols) has established a Public Health Goal of 3 ng/L. OEHHA's Public Health Goals correspond to an increased lifetime cancer risk of 10⁻⁶ (OEHHA, 2006). According to the CDC, Norovirus is the most common cause of gastroenteritis in the U.S. (see Table 3). The infectious dose (LD₅₀) is about 2,700 genome copies (Bui et al., 2013). Norovirus is often characterized as a super molecule; therefore, we can think of this LD₅₀ as 2,700 molecules/L.

As seen in Table 4, these two concentrations have been converted

to a number of units commonly used for chemicals (gallons/L or moles/L) and viruses (particles/L, genome copies/L, or molecules/L). What is immediately evident is that the LD₅₀ for norovirus is 10 to 18 orders of magnitude lower than the *de minimis* level for NDMA (that is, between 10 billion and one quintillion times lower). It seems that Mother Nature's molecule is much more efficient.

At the bottom of the table is a note about the consequences of exposure. In the case of NDMA, the consequence is an increase in the odds of cancer of 10⁻⁶ after 70 years of daily exposure. It may be helpful to remember that the chance of dying from cancer is already roughly one in four. For the one exposed person in a million who suffers this fate, it is his or hers alone. There is no risk of cancer to friends or family, beyond the increased risk of 10⁻⁶ they already have (presuming they are also drinking the water). Nonetheless, the presence of NDMA at measurable levels tells us this water is not in its natural state, which is a situation most would prefer to avoid.

On the right side of the table is Norovirus. For anyone who drinks water with 2,700 virus particles in it, odds are about 50/50 for contracting 48 hours of acute gastroenteritis. The Norovirus experience is not pleasant (Crittenden et al., 2012). It is usually accompanied by intense vomiting and diarrhea. To make matters worse, unless the person who becomes ill has superhuman hygiene, several family members will usually share the same experience in the following days. Only a small fraction (0.003 percent) of people who become ill from Norovirus die, usually from ancillary complications. Nevertheless, it is an experience most would go out of their way to avoid.

By all measures of concentration, the LD₅₀ for Norovirus in Table 4 is many orders of magnitude lower than the *de minimis* level for NDMA, yet the consequences of exposure to Norovirus at these low levels are unpleasant. If we are serious about potable reuse, we should continue to invest in understanding the science behind pathogens and their measurement and control.

Summary

Conquering waterborne disease was one of the greatest accomplishments of the Twentieth Century. Beyond treatment, our Twentieth Century paradigm was to seek natural water sources that had not been contaminated. The trace organic compounds we now see in drinking water are harbingers of a new era where the growth of population and commerce make the natural water paradigm increasingly unworkable.

Where trace organic chemicals are concerned, a new paradigm is needed for safe water. Ultimately, conventional regulations must be expanded to more effectively address impaired sources, but our traditional approach of risk assessment and regulation is too cumbersome to deal effectively with this new age. We should examine the Precautionary Principle to see if we can implement a more proactive approach.

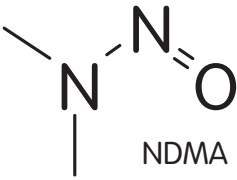
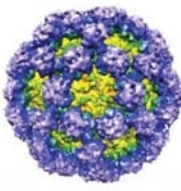
Four guidelines are offered for the new era:

1. We agree that we would prefer not to have these chemicals in our environment or drinking water.
2. We recognize this first principle is not universally achievable; therefore, we need a screen to help make decisions before settled science is available.
3. In water treatment, we should seek continuous improvement, implementing affordable broad-spectrum treatment technologies as they become available.
4. We should find substitutes for compounds that persist in the environment, giving priority to those with adverse effects.

For this new era, we need *de minimis* guidelines to help us sort the wheat from the chaff in the public forum. Benchmarks exist that can be used to develop these guidelines, but formalizing them will require investment.

Finally, while it is the trace organic chemicals that capture our imagination, pathogens remain the most important threat to public health.

Table 4: Comparison of the *De Minimis* Level for NDMA with the LD₅₀ for Norovirus

Parameter	<i>N</i> -nitrosodimethylamine (Manmade)	Norovirus (Nature-Made)
Contaminant of concern		
Mass/L	3×10^{-9} g/L	2×10^{-17} g/L
Molarity	4×10^{-11} mol/L	4.5×10^{-21} mol/L
Particle density	2.4×10^{13} molecules/L	<i>2,700 gc (molecules)/L</i>
Consequence of exposure	Increase in cancer risk of 10^{-6} after 70-year exposure	50-percent risk of acute gastroenteritis after one exposure

Note: The most common expression of the value is in ***bold italics***.



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The 2013 Clarke Prize Honoree

R. RHODES TRUSSELL, PH.D., P.E., BCEE, NAE

Civil and environmental engineer R. Rhodes Trussell, Ph.D., P.E., BCEE, NAE, is the twentieth recipient of the NWRI Athalie Richardson Irvine Clarke Prize for excellence in water research. Trussell is Chairman and Chief Executive Officer of Trussell Technologies, Inc., an environmental engineering consulting firm based in Pasadena, California.

Trussell was selected as the 2013 recipient because of his extraordinary accomplishments in using fundamental scientific principles and current research findings to solve the most challenging water quality problems and improve the designs of new water treatment plants and technologies.

Trussell has worked for over 40 years as a consulting engineer. Unique within the industry is his unusual breadth of expertise, as he is considered an authority on a vast number of treatment technologies, ranging from conventional treatments such as filtration, disinfection, and biological processes, to advanced treatment such as membranes and advanced oxidation. He is the author of peer-reviewed articles and technical reports on all of these topics, including the textbooks *MWH's Water Treatment: Principles* and *Design and Principles of Water Treatment*.

He has also worked on hundreds of water and wastewater engineering projects across the globe, and has developed the process design for treatment plants ranging in size from 1 to 900 million gallons per day in capacity. Because his focus is on implementing practical solutions to improve water quality and meet regulatory and public health needs, his efforts have resulted in better water policy and the widespread adoption and acceptance of many new treatment technologies.

A notable example involves his extensive work with the Contra Costa Water District in Concord, California, in the early 1980s to develop disinfection alternatives to meet new regulations for trihalomethanes (THMs). Disinfectants like chlorine are used to control microbial contaminants in drinking water. However, these

disinfectants can react with naturally-occurring organic matter or bromide in raw water to create disinfection byproducts, such as THMs (many of which are considered carcinogenic). The Contra Costa studies were among the first to demonstrate the cost-effectiveness of chloramination in controlling THM formation. Because of these efforts, the California Department of Public Health agreed to allow the use of chloramine to manage chlorine residual in treated water. Numerous other utilities throughout California followed this model, which was duplicated in nearly one-third of the water supplies in the U.S.

More recently, Trussell has been engaged in assisting water and wastewater utilities with managing complex water supply projects involving the use of advanced treatment technologies for applications such as desalination, groundwater replenishment, and potable reuse.

He has also taken the lead on a groundbreaking project funded by the WateReuse Research Foundation to develop treatment process combinations necessary to employ the direct potable reuse of highly purified wastewater as a new and reliable method to meet future water needs. One of the outcomes of this project is a 2013



report by an NWRI expert panel on *Examining the Criteria for Direct Potable Reuse*.

Because of his considerable knowledge and expertise, Trussell has been invited to serve on numerous prominent boards and committees throughout the water industry. For instance, he served as Chair of the Water Science and Technology Board for the National Academies, Chair of the Research Advisory Committee for the WaterReuse Research Foundation, and Chair of the Editorial Advisory Board for Standard Methods for the Examination of Water and Wastewater. He was also active with the U.S. Environmental Protection Agency's Science Advisory Board for 17 years, including serving as Chair of the Committee on Drinking Water.

At present, Trussell serves on the NWRI expert panel to review the development and implementation of the Orange County Water District's Groundwater Replenishment System, the largest indirect potable reuse project of its kind in the world.

He is also Chair of the National Research Council Committee on Water Reuse, which published the report *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater (2012)*. A major finding in the report was the conclusion that available technology can reduce chemical and microbial contaminants in recycled water to levels comparable to or lower than those present in many current drinking water supplies. Trussell has led the effort to disseminate the findings of this report, which is helping to advance water reuse practices in the U.S.

Trussell will donate the \$50,000 award to his alma mater, the University of California, Berkeley, to support the Trussell Fellowship in Environmental Engineering, which was established by his family in 1991. The fellowship provides annual financial support to one or more outstanding graduate students in the Environmental Engineering Division of the College of Engineering.



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*for Outstanding Achievement
in Water Science and Technology*

The 2013 Clarke Prize Lecture, *How Safe Is Safe in the Treatment of Drinking Water for the Public?* by R. Rhodes Trussell, Ph.D., P.E., BCÉE, NAE, of Trussell Technologies, Inc., Pasadena, California, was presented on Friday, November 15, 2013, at the Twentieth Annual Clarke Prize Award Ceremony and Lecture, held at the Island Hotel Newport Beach in Newport Beach, California.

The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize research accomplishments that solve real-world water problems and to highlight the importance of and need to continue funding this type of research. Dr. Trussell was the twentieth 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. The Joan Irvine Smith and Athalie R. Clarke Foundation provide funding for this award.

More information about the Clarke Prize can be found at www.CLARKEPRIZE.COM.

NATIONAL WATER RESEARCH INSTITUTE

18700 Ward Street

Fountain Valley, California 92708

(714) 378-3278 ♦ Fax: (714) 378-3375

WWW.NWRI-USA.ORG

NWRI Clarke Prize

NOVEMBER 15, 2013

“On the Shoulders of Giants”

~Isaac Newton

I am truly honored to receive the NWRI Athalie Richardson Irvine Clarke Prize and am more than a bit humbled when I consider the previous recipients, who include most of my mentors and many of the colleagues I most admire. It is a heavy thing to receive an invitation to join this group.

Along with the rest of the water industry, I am eternally grateful to Mrs. Joan Irvine Smith and to her family for their vision in creating and sustaining NWRI's Clarke Prize, which, over the past two decades, has become the most valued prize in the water arena and helped immensely to bring water issues to the forefront, where they belong.

John Donne said, “No man is an island.” Where I am concerned, this is especially true. I stand on the shoulders of those who taught me both in class and by example, and virtually all the work I have done has been done in collaboration with others who often contributed more than I.

First, I owe a great deal to the exceptional education I received at the University of California, Berkeley. I was fortunate to be there when Percy McGauhey, Erman Pearson, Warren Kaufman, Bob Selleck, David Jenkins, and Jerry Thomas were all there at the same time. I owe a lot to each of them. David and Jerry are still with us, but Percy, Erman, Warren, and Bob live on in everything I do.

I also owe a great deal to the people at James M. Montgomery Consulting Engineers, Inc. (JMM), who had the guts to hire a young Ph.D. who wanted to do consulting and who took the risk of giving him great responsibility early in life. I owe a particular debt to Bud Carroll (an outstanding leader of men), the late Paul Hennessy (a brilliant engineer I wanted to emulate), and Brian Stone (who gave me one opportunity after another to try something new).

My collaborators while I was at JMM (now MWH) are the ones who really made it all happen. There are too many to name. Notable among them were Carol Tate, Mike Kavanaugh, Marco Aieta, Larry Leong, Andy Eaton, and Issam Najm.

I have also had collaborators and mentors in academia. Most notable among the collaborators is Vern Snoeyink, whose technical depth, patience, and good judgment have done more for me than he will ever know. I am also particularly thankful to Werner Stumm, Jim Morgan, and Charlie O'Melia.

Jerry Gilbert, Jim Manwaring, the late François Fiessenger, and Paul Reiter stretched me in new areas, encouraging me to expand my horizons and engage the international arena.

My collaborators on the MWH textbook, John Crittenden, David Hand, Kerry Howe, and George Tchobanoglous, are a fabulous team. I am really proud of that book. It is way better than anything any of us could do alone.

Also, I would like to thank my family at Trussell Tech. I am so lucky, after 31 years at MWH, to launch a new career where I have the opportunity to work with such a talented group of young people who are all committed to creating a new kind of water business – one dedicated to the idea that good science makes for great engineering.

Most of all, I am thankful to my family: my Mom and Dad, who made me who I am and who sent me off to Berkeley in the early 1960s, having guts to leave me there even when Berkeley was in the news every night; as well as my wife, Liz, and my children, Shane and Bryan, who suffered my absence more than I would like to admit. It's wonderful that all of them, including my daughter-in-law, Céline, have joined me in our excellent Trussell Tech adventure.

Surely, I am the luckiest man alive. I have Liz, the perfect wife. I have Shane and Bryan, two perfect sons – and they married Céline and Lynde, two perfect women who are the mothers of three perfect grandchildren: James, Leela, and Miya. And now the Clarke Prize!

~ R. Rhodes Trussell
NEWPORT BEACH, CA