National Water Research Institute

Presents

The 2017 Clarke Prize Lecture

A Biologist to Engineers, and an Engineer to Biologists

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Abstract

Approaching the solutions to national and global water problems – particularly at the intersection with public health – requires a transdisciplinary approach. In assessing and controlling risks to the public from pathogens in water, I have endeavored to undertake such syntheses. In doing so, I have greatly benefited from the transdisciplinary paths inspired by my intellectual and professional mentors and colleagues.

Challenges with pathogens remain, even in developed countries, despite over a century of advances. Concerns from inhaled pathogens are increasing. The role of the water environment in staunching the rise of antibiotic resistance and the impact of climate change on water-related infectious diseases are significant twenty-first century problems. As we reinvent our aging infrastructure by maximizing water, energy, and nutrient recovery, we must not lose sight of the critical role of water management to public health. These challenges will be met by building upon the foundations of those who preceded us and integrating tools from other disciplines into our approaches.

As a professor, it is also my obligation to educate and prepare the next generation for the challenges we will face. Our educational and research institutions will be tested to broaden the preparation of future water professionals. As Louis Pasteur stated, "Chance favors only the prepared mind."

1. Introduction

In 1994, inaugural Clarke Prize recipient Bruce Rittmann wrote about the two "kingdoms" of water science and water technology. I chose to return to and expand upon that theme throughout my Lecture. It is clear that the solution to water problems has and still requires the transdisciplinary integration of knowledge. Those working in the water field have long practiced drawing from a multitude of disciplines, and I will illustrate this interdisciplinary approach with respect to both teaching and research issues of the past and future.

I took the title of my Lecture, "A Biologist to Engineers, and an Engineer to Biologists," from a description that I recollect my own doctoral mentor, Richard S. Engelbrecht, applied to himself, and which has applied to my personal trajectory. I have approached biological problems at the interface with human health using the quantitative tools of engineering.

1.1 My Intellectual Journey

When I entered the Illinois Institute of Technology (IIT) as a biology major, the courses at my high school allowed me to jump into differential equations, which was unusual for a recent high school graduate. At IIT, we were required to take a number of chemistry courses. The end of my freshman year coincided with the first Earth Day, which was influential in my thought processes. Early in my undergraduate career, I was not a particularly distinguished student; I did not see the connections between the classroom subjects and the environmental issues I was interested in.

During my junior year, I was fortunate to work in the research laboratory of a limnology professor in the Biology Department. This opportunity led to elective courses in IIT's environmental engineering program. Roger Minear, Ray Letterman, and Jim Patterson introduced me to the world of water and wastewater – and I was hooked. I now saw a way to apply my scientific education to real problems.

Jim Patterson recruited me to join the MS program in environmental engineering. I learned a great deal about industrial pollutants, biological treatment processes, and the emergent policy background of water quality protection and control. A key contact that I made from my MS thesis was Cecil Lue-Hing, at the time the Research and Development Director of the Metropolitan Sanitary District of Greater Chicago (MSDGC). It was during my MS program that I took my only course in biostatistics.

After completing my MS degree, I decided to look at other universities for my doctoral program. In the pre-internet days, I had access to little information about doctoral programs. I applied to a number of the top programs in the country and ultimately decided, after visiting the campus, to undertake my doctoral work 120 miles south of IIT at the University of Illinois at Urbana-Champaign and take up a research assistantship with Dick Engelbrecht.

In retrospect, I could not have asked for a better research mentor. With a crossover background from zoology into environmental engineering, Dick steered me towards a concentration in microbiological research. Part of this research was on the presence and treatability of mycobacteria in water (Englebrecht et al., 1979), which remains a current interest of mine. I also was deeply immersed in the performance of chlorine and its compounds as disinfectants, as well as the relationship between disinfection kinetics and chemistry. Dick gave his students substantial independence and opportunities to interact with key researchers at the U.S. Environmental Protection Agency (USEPA). This freedom was out of necessity for Dick, who was engaged in the leadership of the then-called Water Pollution Control Federation. It was due to Dick's tutelage that I was introduced to the studies of the National Academies, specifically when he asked me to assist in doing research as part of the original report on *Drinking Water & Health* (NAS, 1977). My first direct exposure to unplanned wastewater reuse was when we did a sampling campaign in the Salt Fork of the Vermillion River, between the wastewater discharge at St. Joseph, Illinois, and the water intake at Danville, Illinois.

Immediately after receiving my Ph.D., my first faculty position was at Rensselaer Polytechnic Institute. During my 3 years there (1978 to 1981), environmental engineering was part of the chemical engineering department, and I gained a better understanding of the role of process analysis in developing solutions to environmental issues. In addition, a colleague, Harry Bungay, was at the forefront of using personal computers in education and simulation, and I readily took to that technology.

It was a great experience, with great students, including undergraduate and MS student Bruce Logan (a future Clarke Prize winner). Yet, after 3 years in upstate New York, I missed city life.

Once again, Jim Patterson was important in encouraging me to come back to IIT in 1981, this time to join the faculty. While teaching there, I became immersed in the emerging field of hazardous waste management, as well as conducting research on a USEPA center that IIT had received on waste elimination.

1.2 Introduction to Risk Assessment

Shortly after coming back to IIT, I re-engaged with disinfection work through Mark LeChevallier from American Water. At the time, the State of Illinois was proposing to eliminate mandatory wastewater disinfection and, instead, only required disinfection when discharge was within 20 miles of a water intake or during the swimming season when there was a nearby designated recreational use. American Water, which operated the water treatment plant in Peoria, Illinois, about 100 stream miles downstream of IIT, was concerned about adverse effects on source water quality. The Chicago Waterway System and the Illinois River have played great roles in the history of wastewater management in the United States (Cangnon and Glantz, 1996), and this controversy was another example.

As a result, I was retained to provide testimony before the Illinois Pollution Control Board for continuing the disinfection requirement. During these proceedings, I wound up being the adversary of Cecil Lue-Hing and MSDGC. This assignment resulted in me diving into the world of microbial risk assessment and publishing my first papers on the topic in 1983 (Haas, 1983a,b). At the time, I had no idea that the National Academies were on the verge of publishing the "Red Book" on risk assessment (NAS, 1983) – perhaps I was fortunate not to be burdened with that baggage.

Clearly, I did not make too much of an adversary of Dr. Lue-Hing and MSDGC, considering my collaborations and interactions with them have continued throughout my career. In fact, in 1985, at Cecil's suggestion, I was asked to testify before a committee of the Illinois Legislature regarding a large milk-borne outbreak of *Salmonella*. Subsequently, I had the pleasure of working with (what is now) the Metropolitan Water Reclamation District. One of the projects I assisted with was the District's development of disinfection strategies for their three largest plants.

1.3 A Wonderful Collaboration

I acquired a taste for interacting in the public policy arena through work I did on risk assessment for the Illinois River System. A summer fellowship from the American Association for the Advancement of Science to work at the USEPA in 1984 gave me a good sense for how the wheels of policy turn at the federal government. Even more critical was the fact that Chuck Gerba was on the same fellowship that year. While I had been familiar with Chuck's work since graduate school, we had never met, and the summer allowed us to strike up a close relationship.

At the time, Joan Rose was finishing her doctoral work at Arizona with Chuck. Because of our interactions that summer, the three of us ended up collaborating often over the next 30-plus years.

I came to quantitative microbial risk assessment (QMRA) by accident, without having immersed myself in the entire risk analysis field. When I took a sabbatical from 1988 to 1989 at the University of Illinois at Urbana-Champaign, I decided to develop and teach a course in risk analysis. As most academics know, one of the best ways to learn something is to teach it.

It was then time to write a book (Haas et al., 1999). Joan Rose, Chuck Gerba, and I talked about it for a few years. In the mid-1990s, we bit the bullet. I had written one book previously and Chuck had written several, so we had a sense for what it would entail. We decided to publish a book together to help define the field we were developing, drawing on our complementary strengths and interests.

2. Work in Water Reuse

I have lived my life in the Northeast and Midwest. As such, planned water reuse had not been in the forefront of my training though (certainly unacknowledged) unplanned reuse, as in the Illinois River, is quite common; however, I have always regarded the fields of water and wastewater treatment as being parts of a continuum, and I have done research in both contexts.

I was gratified to have an opportunity to serve on my first Committee on Water Reuse for the National Academies from 1996 to 1998. This committee was chaired by Dick Engelbrecht until his untimely passing, then by Jim Crook (NRC, 1998). It became clear that QMRA was one of many tools needed to understand this topic, which is of critical importance in California. Rhodes Trussell, a previous Clarke Laureate, was also on this committee and, as a spinoff, he and I published a conference paper that set the stage for applying QMRA and systematic analysis of multiple barriers to the reliability of reuse systems (Haas and Trussell, 1998). In this report, to the regret of many of the committee members, the characterization of potable reuse as an "option of last resort" was articulated.

Technology advanced and the population pressures for reuse increased to the point where the second National Academies Committee was convened from 2008 to 2011 (which I also served on), and it became clear that potable reuse was now feasible and, in circumstances necessary, could provide adequate protection to public health (NRC, 2012).

By now, I had perhaps become an expert and was asked to be on the recent NWRI Expert Panel that concluded that, in California, it was feasible to regulate direct potable reuse to be adequately protective of public health (Mosher and Vartanian, 2016).

In my opinion, the era of "deliberate," "unintentional," "direct," and "indirect" modifiers to the term "potable reuse" have long since passed. We need to look at water holistically and assess when and how public health, at a reasonable cost and environmental footprint, can be implemented by a particular design. New concepts for the treatment of water to qualities "fit for purpose" and the inclusion of decentralized and onsite supply and treatment of waters and wastewater for reuse are emergent twenty-first century paradigms.

Looking back, I benefited from a solid fundamental education at both the undergraduate and graduate levels, with the breadth to obtain skills in chemistry, mathematics, and toxicology. This understanding, in turn, gave me the grounding to assimilate important concepts from biology, chemistry, statistics, chemical engineering, epidemiology, environmental health, and public policy. I will return to this concept of transdisciplinary learning to discuss how we educate future professionals to solve water problems.

3. From Indicators to Molecular Biology

If there is one thing we know for certain, it is that both the problems and tools available to us in the future will be different from those in the past. It does not mean that past problems and tools will become irrelevant, but that new issues and capabilities will emerge.

From the dawn of water microbiology until the 1980s, the use of culture-based measurements – predominantly of indicator organisms – was the tool at hand. The ability to directly analyze for pathogens using DNA-based technologies emerged in the 1980s with the polymerase chain reaction (PCR). In the late 1990s, quantitative PCR (qPCR) was developed and rapidly deployed as a technique to quantitatively measure DNA in environmental samples; however, qPCR will measure all targeted environmental DNA, whether associated with a viable and infectious pathogen or not. In addition, developing a qPCR assay requires the design of primers, probes, and assay conditions to achieve an acceptable balance of specificity and sensitivity (Reischer et al., 2007; Guy et al., 2003).

The behavior of qPCR versus direct viability measurements is different, which is shown in a study we conducted in cooperation with Mark LeChevallier at American Water, under sponsorship from the Water Environment & Reuse Foundation (WE&RF). Nineteen reuse utilities in the United States were sampled for *Legionella* using culture-based techniques, as well as qPCR and EMA-qPCR, which is claimed to assay for only viable organisms via qPCR (Chen and Chang, 2010). There are clear, significant differences between the three methods – yet which method is most relevant for predicting human health risk is uncertain.

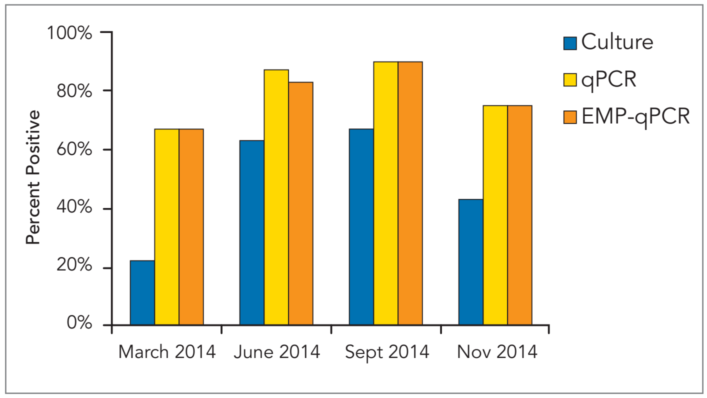

Figure 1. Average percent positive of Legionella *in samples from 19 utilities treating wastewater for reuse using three different assays. Joint project between Drexel and American Water. Graphic from the final report to the Water Environment & Reuse Foundation.*

How we use molecular-derived data to assess human health risk remains an active, open, and important question. The melding of molecular biology with risk assessment will allow more rapid and near real-time assessment of water quality in reuse water, recreational water, and other venues.

In the past 10 years, the use of high throughput sequencing has bypassed the need for using pre-determined primers in PCR- and qPCR-based methods, which can give exquisite insight into the relative community composition. To date, it has not been possible to use high throughput sequencing to quantify microorganisms in samples; therefore, coupling this method to human health significance remains a work in progress. As an example, my student, Kerry Hamilton, working with colleagues at CSIRO in Brisbane, Australia, sampled storage tanks from roof-harvested rainwater (Ahmed 2017), and was able to attain the microbial community profiles in Figure 2.

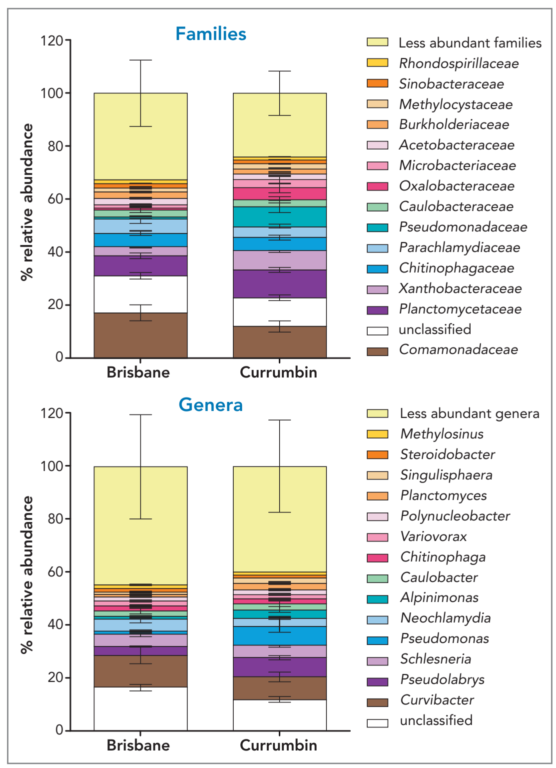

Figure 2. Distribution of the 15 most abundant families and genera among tank water samples collected from Brisbane (n=44) and Currumbin (n = 44) in Southeast Queensland, Australia (Ahmed, 2017).

3.1 Emerging Pathogens

The twentieth century represented a period in which, by water and sanitation, the burden of infectious disease was dramatically reduced. Still, there is a substantial burden of infectious disease that needs to be addressed. Some of these challenges were addressed by a number of prior Clarke Prize Laureates, in both their Lectures and their research, including Mark Sobsey and Joan Rose, but even in developed countries, such as the United States, water-related infectious disease challenges still remain. The crisis in Flint, Michigan, heightened our awareness about *Legionella;* however, this organism is by no means restricted to one venue. The Centers for Disease Control and Prevention (CDC) (Beer et al., 2015) has shown that there is continuing, and perhaps increasing, prevalence of Legionellosis drinking water outbreaks in the United States. It is known that outbreaks only represent a small portion of cases that occur.

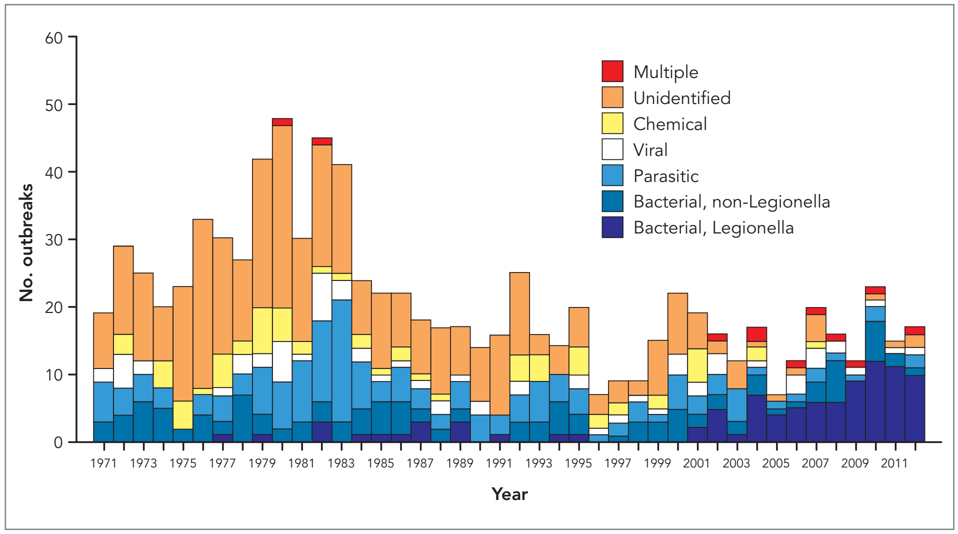

Figure 3. Reported outbreaks of illnesses from drinking water (Beer et al., 2015).

Legionella is only one example of pathogens that can amplify in a variety of wetted surfaces – from drinking water mains to premise plumbing to rainwater storage to cooling towers to ornamental fountains and water features. Ashbolt has used the term "saprozoic" to denote these pathogens, which often amplify in biofilms that contain amoeba (Ashbolt, 2015).

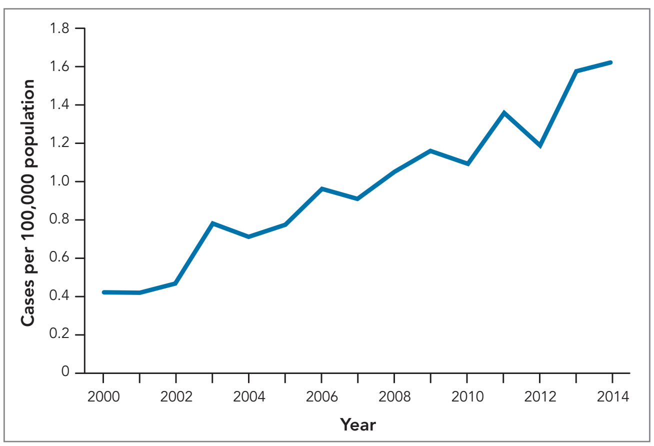

Figure 4. Estimated Legionellosis case rate in the United States by year (Garrison et al., 2016).

Other examples include the pathogens *Campylobacter* and *Mycobacterium.*

These pathogens can cause illness when aerosols are formed and inhaled. The total disease burden in the United States from all the saprozoites is not known; however, for Legionellosis, the total diagnosed case rate is estimated at 1.7 per 100,000 annually and is significantly increasing, as reported by the CDC (Garrison et al., 2016) and shown in Figure 4.

Mycobacterium species are increasing in frequency in potable water in the United States (Donohue et al., 2015). Although the attribution of outbreaks from non-tuberculosis mycobacteria to water are mainly circumstantial, mycobacteria are another class of microorganisms that also can be transmitted by inhalation and dermal contact (Hamilton et al., 2017).

Undoubtedly, there will be more microorganisms that emerge as being potentially transmissible by water, including other than through ingestion. Some may be associated with climate change, which will be discussed in Section 3.3.

3.2 Antibiotic Resistance

Antibiotic resistance is emerging as a major public health concern. For example, as noted by Pruden (2013):

- Carbapenem resistance in *Klebsiella* has risen from 1.6 percent to 10 percent in the United States from 2001 to 2011.
- Over 1-million cases of multi-resistant tuberculosis patients were estimated between 2011 and 2015.
- Methicillin-resistant *Staphylococcus aureus* (MRSA) now represents over 50 percent of *S. aureus* infections in the United States, with half a million hospitalizations per year.

We do not know the extent to which water management may either play a role in the dissemination of antibiotic resistance or be useful in slowing down that dissemination as there are many reservoirs (i.e., animals, humans, environmental) for antibiotic resistance genes (ARGs). Antibiotics are used widely not only in human medicine, but also in veterinary medicine. Many processes exist whereby ARGs can exchange amongst these reservoirs. We need to know the quantitative amounts and the rates and flows amongst reservoirs to ascertain the role of water and, as needed, define control strategies. But we do know that ARGs occur in sludges (Calero-Caceres et al., 2014), reclaimed water (Fahrenfeld et al., 2013), and wastewater (Lapara et al., 2011).

Analyzing these biological problems with an engineering eye will enable solutions to be developed, whether in the water sector or elsewhere.

3.3 Climate Change

It is recognized widely within the water industry that climate change impacts the quantity of water, thereby directly affecting the long-range planning of utilities in Southern California and elsewhere. What may be less widely recognized is the impact of climate change on water quality (including microbial water quality) and the resulting impacts on human health.

Seventeen years ago, Joan Rose and her colleagues analyzed the occurrence of reported drinking water disease outbreaks, and they found an association with preceding precipitation events (Rose et al., 2000). My interest in the relationship between weather and infectious diseases became piqued a few years later, when I was approached by a then-colleague in our school of public health to look at Legionellosis cases in suburban counties. Using epidemiological tools, we discerned that although cases increased in the summer, humidity was a better predictor than temperature at correlating with occurrence (Fisman et al., 2005). Recent systematic reviews have buffeted the association between climatic factors and infectious disease risks (Levy et al., 2016).

Climate change factors that could alter pathogen occurrence include temperature, precipitation, humidity, and wind-blown dust. Impacted microorganisms include bacteria, viruses, and protozoa. In addition, changes in water flows and temperature may alter the host ranges for insects that can serve as pathogen vectors. Water managers need to be attuned to these factors (Wu et al., 2016). One concrete question is: could it be that the combined effects of overland flows and increased temperatures in some watersheds might require additional pathogen log removals to be installed?

With this question and others in mind, it is obvious that there is a need for much better quantitative models to determine the magnitude of these impacts and inform what might be major long-term management and engineering decisions.

3.4 Reinvention of Aging Infrastructure and Net Zero Concepts

Some of the earliest concerns for human management of the water cycle were focused on quantity – getting enough water where it is wanted, and removing water and wastewater where it is not wanted. Then, water management progressed towards the removal of contaminants detrimental to human health and the environment.

With the increasing movement for wastewater reuse, of which Southern California and NWRI were leading advocates and proponents, we have moved towards a circular economy of water. A number of prior Clarke Prize Laureates (Logan, Sedlak, and others) have discussed how materials (e.g., nutrients) and energy also can be recovered. Ultimately, in a technological sense, looking at footprints for near-zero discharge (Tong and Elimelech, 2016) and near net-zero energy (Yan et al., 2016) is foreseeable. It may even become feasible in less water-stressed regions, such as the northeastern United States; however, because much of our urban water infrastructure, particularly in older cities, is in need of reconstruction, the opportunity to reinvent using these new paradigms must be considered.

The optimal balancing point between net-zero energy systems and zero discharge systems needs to be assessed from the overall point-of-view of social costs; however, we must not lose sight that the protection of public health (including from waterborne pathogens) remains a key objective.

There are little data on pathogen removals from innovative energy and materials recovery systems. These data are necessary to ensure that we do not increase public health risks. The intersection of the circular water, energy, and nutrient economy with public health, in part by using QRMA tools, is necessary. Recent work combining QMRA with lifecycle assessment points to an encouraging direction within this context (Kobayashi et al., 2015).

4. Whither QMRA?

QMRA is an evolving field of practice, which means there are new problems to tackle. In 2015, I reviewed the evolution of modeling in QMRA and identified a number of data gaps (Haas, 2015). We need more data on dose-response from other classes of microorganisms, particularly helminths, pathogenic vegetative protozoa (*Acanthamoeba*, *Naegleria*), and fungi (such as *Cryptococcus*).

We also need more collaboration with mathematical epidemiologists to understand the linkage between QMRA and transmission models of contagious diseases. A disconnect exists between how incubation time is modeled in disease transmission models (Eisenberg, 2005) and what we know from incubation time distributions from deliberate animal and human trials (Huang and Haas, 2009). A recent Ph.D. graduate from my group, Bidya Prasad, has helped advance knowledge in this area.

We need to bring the tools of molecular biology to bear in understanding the pathogen-host interaction, which could lead to classes of models for QMRA akin to the pharmacokinetic models used in chemical risk assessment (Weihsueh et al., 2007).

5. How We Educate

In 1976, I was told by a former dean of mine that, in 25 years, there would not be any need for environmental engineers because all the environmental problems would be solved. But current technology and practice will not solve all of our environmental problems – neither in environmental engineering nor in water science. As educators, we can train students and young professionals to solve problems at a rate that is faster, hopefully, than the creation of further problems.

What kind of students and young professionals should these problem-solvers be? I offer two thoughts to ponder, which represent challenges to the technical education profession.

First, we can look at the skills needed to solve water problems now and in the future. James Morgan, a prior Clarke Prize Laureate, used the metaphor of a stream to describe the advances in water quality science and technology in his 2004 Abel Wolman Lecture at the National Academies. I would like to modify that metaphor now to describe how different domains of knowledge were incorporated in advancing water quality. The early years of progress in water knowledge required incorporating basic principles from hydraulics, geography, hydrology, and fluid mechanics. Progressively, over the end of the nineteenth and early twentieth century, additional water knowledge needed to be incorporated. As we approach the third decade of the twenty-first century, we see ever more sophisticated knowledge being incorporated to understand and solve water problems. In addition, the rate at which new domains of knowledge need to be absorbed is increasing. This acceleration in the rate of new disciplines is what Toffler, nearly 50 years ago, termed “future shock” (Toffler, 1990).

Clearly, no single person can truly assimilate the details of all the necessary tributaries to this stream of knowledge. Over time and with a good grounding of fundamentals, one may be able to incorporate more of the different skills into a toolbox, but it is critical that there is basic educational preparation that enables us to understand what each tributary brings to solving actual water problems.

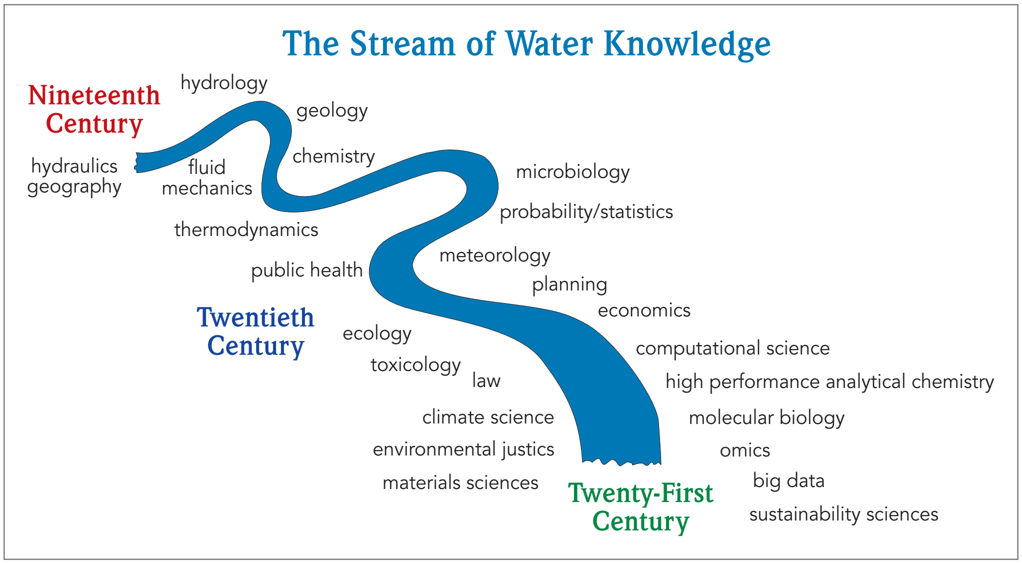

Figure 5. The "Stream of Water Knowledge." Adapted from the 2004 Abel Wolman Lecture of James Morgan.

Over the past decade, especially in the engineering field, the concept of educating a "T-shaped" professional has emerged. Uhlenbrook and de Jong have described this concept in the context of educating water professionals (Uhlenbrook and de John, 2012): that students have great depth and expertise in a particular discipline (say environmental engineering, chemistry, microbiology, or sustainability), as represented by the vertical of the "T," and that students have enough breadth of knowledge of the other disciplines to communicate with other experts, as represented by the horizontal of the "T" (Figure 6). With this preparation, those who have depth and expertise in the other domains are able to communicate and interact with each other, as shown on the right of Figure 6.

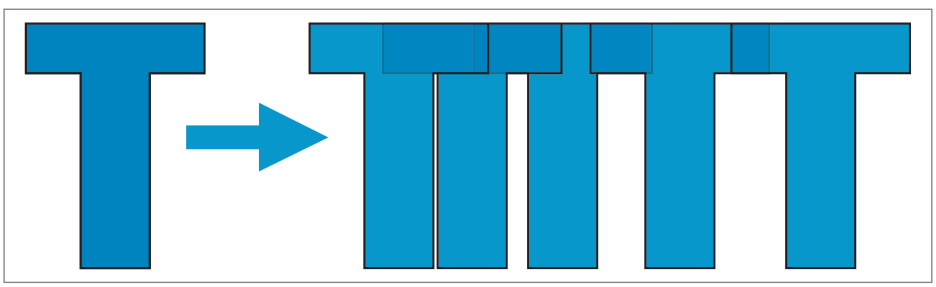

Figure 6. Concept of a "T" shaped individual and a team of "T" shaped individuals.

In the United States (especially in the engineering field), there are barriers to fully realizing these educational objectives. Too often, the accreditation agencies require depth in multiple areas at the sacrifice of breadth. Those who work in interdisciplinary and transdisciplinary problems, such as water, need to push back on efforts to reduce curricular breadth. We need to enable educators to provide future leaders of the water profession.

6. Coda

Entering college in 1969, I could not have predicted the path that I have taken over the last 48 years. It is clear that my undergraduate and graduate education provided a good grounding of the fundamentals on which I have built. I have been fortunate to have used novel solutions as they arose to extend my palette of skills.

I happen to share a birthday with Louis Pasteur, who wrote "Chance favors only the prepared mind." By being prepared with good fundamentals and having outstanding mentors, I have had the advantage of seizing the chances that have arisen before me.

7. Acknowledgements

I am grateful to my late cousins, Drs. Norman and Murray Jarvik, for inspiring me towards a research career, and to my late parents, Louis and Gertrude Haas, for providing me the inspiration for an education in a house full of books. My mentors, Jim Patterson and the late Dick Engelbrecht, were important in guiding me into environmental engineering and teaching me in formal and informal ways about the profession. My wife, Victoria, has been incredibly supportive of my work, which has taken me around the globe.

Joan Rose and Chuck Gerba have been remarkable collaborators over the decades and have been so much fun to work with.

Both Cecil Lue-Hing and Rhodes Trussell have been important to my development, grounding me to practical issues that face the water industry.

I have had a remarkable set of students in this work, too many to name individually. All my Drexel doctoral graduates, more recently Kerry Hamilton, Bidya Prasad, Michael Ryan, Yin Huang, Mark Weir, Joanna Pope, Tim Bartrand, and Chris Crockett, have helped me in this work. I have had significant support from the National Science Foundation (NSF), Water Research Foundation, Water Environment & Reuse Foundation, and Philadelphia Water Department.

I acknowledge my faculty colleagues at Drexel and the late Leroy Drew Betz, who endowed the professorship at Drexel that I have held and has provided me with much flexibility in pursuing my research and professional endeavors.

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The 2017 Clarke Prize Honoree

Charles N. Haas, Ph.D.

LD Betz Professor of Environmental Engineering

Head of the Department of Civil, Architectural & Environmental Engineering

Drexel University

Dr. Charles N. Haas received the NWRI Athalie Richardson Irvine Clarke Prize in 2017 for his outstanding work in pioneering and applying methods to assess and minimize health risks caused by exposure to disease-causing microorganisms (referred to as pathogens) in water and wastewater. Haas is the LD Betz Professor of Environmental Engineering and Head of the Department of Civil, Architectural, and Environmental Engineering at Drexel University in Philadelphia, Pennsylvania.

Haas received the Clarke Prize on October 19, 2017, at the Twenty-Fourth Annual NWRI Clarke Prize Lecture and Award Ceremony, a black-tie event held at the Irvine Marriott Hotel in Irvine, California.

Trained in both engineering and microbiology, Haas used his cross-disciplinary education to explore the disinfection and inactivation of pathogens in water for the last three decades. His most widely cited textbook, *Quantitative Microbial Risk Assessment* (1999), was the first complete guide for measuring and evaluating the risks to humans posed by disease-causing organisms in food, water, air, and other environmental routes. As used today, quantitative microbial risk assessment (QMRA) involves hazard identification, dose response, exposure assessment, and risk characterization. This valuable, widely used tool has influenced the development of public health guidance and policies by prominent organizations both nationally and internationally. Today, Haas is known as the "Father of QMRA."

The U.S. Environmental Protection Agency has cited Haas' research in the Surface Water Treatment Rule and its iterations (including the Long Term 2 Enhanced Surface Water Treatment Rule) and Ground Water Rule (2006). Haas also used his expertise in QMRA to help the World Health Organization develop both the *Guidelines for Drinking Water* and *Guidelines for the Safe Use of Wastewater, Excreta, and Greywater*. Among his more recent work, he served on the NWRI Expert Panel for the State of California (which looked at both regulations for indirect potable reuse using surface water augmentation and the possibility of developing regulations for direct potable reuse) from 2014 to 2016.

"There is no other individual I know who has contributed more or has had the impact of Chuck Haas at advancing quantitative science within the engineering profession," said colleague Joan Rose, Ph.D., the Homer Nowlin Endowed Chair for Water Research at the University of Michigan, and recipient of the 2016 Stockholm Water Prize. "Chuck has always pushed traditional boundaries, not only for himself, but for others to think about new interfaces. He continues to promote the idea that we can answer the question of 'What is safe?'"

The

ATHALIE RICHARDSON IRVINE

Clarke Prize

for Outstanding Achievement

in Water Science and Technology

The 2017 Clarke Prize Lecture, *A Biologist to Engineers, and an Engineer to Biologists,* was prepared by Charles N. Haas, Ph.D., the LD Betz Professor of Environmental Engineering and Head of the Department of Civil, Architectural & Environmental Engineering at Drexel University, Philadelphia, Pennsylvania. He presented the Lecture on Thursday, October 19, 2017, at the Twenty-Fourth Annual Clarke Prize Award Ceremony and Lecture, held at the Irvine Marriott Hotel in Irvine, 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. Haas was the twenty-fourth 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 & Athalie R. Clarke Foundation provide funding for this award.

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

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