

# *National Water Research Institute*

*Presents*

The 2006 Clarke Lecture

## Disinfection Byproducts in Drinking Water: Additional Science and Policy Considerations in the Pursuit of Public Health Protection

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The subject of my remarks today, that of disinfection byproducts (DBPs) in drinking water, is a subject that I have worked on for the better part of my career. It is also a subject that has captured the interests of water scientists, engineers, and policy-makers for the past 32 years.

DBPs have been a focal point for those associated with water supply and the water-works industry because DBPs originate with the manner in which we produce drinking water from natural groundwater and surface water supplies. DBPs originate from our practice of disinfection, a process in which we inactivate disease-causing microorganisms present in

our raw water supplies to protect public health. In so doing, we generate byproducts that have been associated with adverse health effects, notably bladder cancer, spontaneous abortions, and birth defects. Few issues in our professional lifetime have had such an impact on raw water source selection, watershed management, water treatment plant design and operation, and the distribution of finished drinking water as the issue of DBPs.

Today, I want to discuss three themes associated with DBPs in drinking water:

- The role of utilities in epidemiological studies.
- Shortcomings in our approach to regulating DBPs.

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- The need to implement more effective management strategies and control technologies to limit the formation of DBPs.

### **Epidemiological Studies and the Role of Water Utilities**

The presence of DBPs, notably chloroform and other trihalomethane (THM) species, in finished drinking water was first reported in 1974 (Rook, 1974) and was linked to chlorination, a common water treatment practice (chlorine is traditionally applied as an oxidant of undesirable chemical impurities and as a disinfectant of pathogenic microorganisms). Shortly thereafter, several epidemiological studies suggested a link between the chlorination of water and cancers of the digestive and urinary tracts (e.g., National Cancer Institute, 1976). This ultimately led to the regulation of THMs in our drinking water in 1979 (U.S. Environmental Protection Agency, 1979). Since that time, numerous additional epidemiological studies (National Academy of Sciences, 1987; Morris et al., 1992) have shown an association between bladder cancer and DBP levels in drinking water, validating the need to regulate these byproducts.

Because of the linkage between bladder cancer and elevated levels of DBPs (represented by the concentration of THMs), the regulation of these byproducts has been directed at lowering lifetime exposure to these compounds. Accordingly, the structure for these regulations is an annualized average concentration based on samples taken quarterly (i.e., every 3 months) at four locations in the distribution system for each water treatment plant servicing consumers. Since the discovery of THMs in finished drinking water and the establishment of the 1979 regulation, THM concentrations in drinking water have decreased by 90 to 95 percent in some systems.

While the regulation of DBPs on an annualized average basis is rational for a chronic disease such as bladder cancer, the paradigm changes for acute adverse health effects (i.e., health effects associated with short-term exposure). Over the past 15 years, several studies have suggested an association between DBPs in drinking water and adverse reproductive outcomes, including spontaneous abortion, neural tube defects, and intrauterine growth retardation (Bove et al., 1995; Waller et al., 1998; Klotz et al., 1999). Although these studies report



modest risks, even low-magnitude risks are of potentially great public health importance because of the ubiquitous nature of DBP exposure in public water supplies. If, indeed, there are adverse reproductive outcomes due to acute exposure to DBPs in drinking water, this will mean that the traditional paradigms for monitoring and regulating DBPs will have to change.

It is widely acknowledged, however, by epidemiologists and other scientists, that most epidemiological studies involving DBPs in drinking water (particularly those involving acute exposure) suffer from the misclassification of exposure (Reif et al., 1996). This means that the levels of DBPs assigned to the subjects in these studies may not be properly characterized.

One reason is that water distribution systems are complicated networks. Many have multiple sources of treated water at various entry points into the system. Additionally, most distribution systems have finished water storage facilities, and water supply, demand, storage, and flow patterns change throughout the day. Hence,

one can expect significant spatial and temporal variations in DBP levels throughout the distribution system (Singer, 2001). As noted earlier, most water utilities measure DBP concentrations quarterly at a small number of locations in their distribution systems. Accordingly, DBP data are temporally and spatially sparse and, because of the complexity of distribution system networks, it is difficult to know with any degree of certainty the


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distribution of DBPs in the tap waters of the subjects in these epidemiological studies. While this is not the only source of exposure misclassification in epidemiological studies, it can be a major one.

Most importantly, many of the scientists conducting these epidemiological studies do not work directly with the utilities whose waters are being investigated. Often, investigators rely on centralized compliance monitoring data that are reported to the State and, therefore, are not aware of factors such as the manner in which the data were collected, the timing of data collection, and the location of data collection points, water quality and



treatment considerations that may have impacted DBP levels, and distribution system flow patterns. The data are taken as being representative of the system as a whole, whereas in fact they may not be. Often, the assignment of DBP levels is made using system-wide, quarterly average values, and we know this to be an invalid representation of exposure. In more “sophisticated” studies, the subjects are located on a Geographic Information System (GIS) map and are assigned DBP levels based on distance to the nearest sampling point, using distances “as the crow flies.” But crows do not fly through water distribution systems, and this method also leads to exposure misclassification.

Had the investigators consulted with operations personnel at the utilities in question and given the same degree of attention to the water quality data as was given to gathering the health effects data, exposure classification would have been more credible and the findings more robust. Local water utility personnel are the ones that know the most about their system — demand patterns, flow patterns, water ages (residence times) associated with different

sampling locations, water quality and treatment variations, and so on. They should be consulted when exposure is assigned and be involved in the final analysis to ensure that the data provided are being used and interpreted properly.

At the University of North Carolina (UNC), we recently completed a major epidemiological study of DBPs in drinking water and adverse pregnancy outcomes (Savitz et al., 2005).

### **Major New UNC-Based Drinking Water Study Suggests Pregnancy Fears May Be Overstated**

Fears that chemical byproducts resulting from purifying drinking water with chlorine boost the chances that pregnant women will miscarry were not supported by the results of a major new study. If such threats exist at all, which is uncertain, they likely are modest, it concludes.

The national study, directed by University of North Carolina at Chapel Hill scientists, contrasts with earlier, less detailed work done in Northern California and published in 1998. That research suggested an association between byproducts known as trihalomethanes and loss of pregnancy.

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The principal investigator on the project was an epidemiologist, but water quality engineers and scientists were part of the project team from the outset. We took great care in the design of this prospective study because most



previous studies of this type, as noted earlier, suffered from the misclassification of exposure. Water quality specialists worked with the water utilities in selecting appropriate sampling points in the utilities' systems, gathered water quality data that was contemporaneous with the gathering of health effects data, and assisted health effects specialists in interpreting DBP information for use in the final epidemiological analysis. The water utilities played a key role in this 5-year study. They provided information concerning their distribution systems, collected water samples, informed us when major changes in water quality or treatment took place, and provided residual chlorine and chlorine dose information and their own DBP data for quality assurance purposes. Without their assistance, the study could not have been done properly. The result was a study with a more robust experimental design and conclusions that are more scientifically sound and defensible than previous studies of this type.

I would encourage all health scientists conducting research on drinking water quality to involve water quality scientists and engineers as part of their project teams and to enlist the support of the waterworks industry

in conducting their investigations. Water utility personnel, as a general rule, are anxious to participate and have a clear role to play in such studies. Likewise, I would encourage all primacy agencies, when contacted for data by scientists interested in conducting health effects research on drinking water, to encourage the scientists to interface with local utilities that provide these data to better understand their meaning and significance. While such an approach may take more time and effort, the results will have a firmer basis. Lastly, I would encourage all of us water supply professionals, researchers, and practitioners alike, to seek involvement in such studies. We are all in the same business – providing safe drinking water to the public. We are committed stakeholders to public health protection. If there are issues associated with the safety of our drinking water, we want to know about it so corrective action can be taken.

### **Shortcomings in Our Approach to Regulating DBPs**

As noted earlier, DBPs in finished drinking water have been regulated since 1979 (U.S. Environmental Protection Agency, 1979). For reasons that are not entirely clear, the original



regulation of THMs was based on the sum of the concentrations of all four species (chloroform, bromodichloromethane, dibromochloromethane, and bromoform), perhaps because the health effects of each of the individual species were not known at the time. Moreover, the sum of the concentrations was on a weight basis (i.e., adding the milligrams per liter [mg/L] concentrations of each of the four species) despite the well-known fact that the molecular weights of the species increase with increasing bromine content. In comparison to summing the concentrations on a molar basis, this effectively gives a higher weighting factor to chloroform, a species that we now know to be of lesser concern from a health effects standpoint than its bromine-containing THM counterparts. A more prudent course of action would have been to regulate the THMs on a molar basis, but this was not done in 1979.

What is most disturbing is that, once this precedent was set in the 1979 Rule, subsequent versions of regulations for DBPs have continued in this manner. We see this in the Stage 1 Disinfectants/Disinfection Byproducts Rule (U.S. Environmental Protection Agency, 1998) in which the regulation of DBPs extends to a new major class of chemicals. The Stage

1 Rule not only continues to regulate the sum of the four THM species on a mg/L basis, but also regulates the sum of five haloacetic acids (HAAs) on a mg/L basis which, in essence, again gives lower weight to the bromine-containing haloacetic acid species. The molar concept is not a difficult concept. It simply involves dividing each of the mg/L concentrations by the molecular weights of the respective species. This can be simplified, if necessary, for utility personnel who are not chemically oriented by developing a simple algorithm or spreadsheet that will do the calculation for them in much the same way as spreadsheet calculations are now made for CT compliance. A mistake was made in 1979. Why should it have been continued and extended in 1998, almost 20 years later, and why should it have carried further into the recently finalized Stage 2 Disinfectants/Disinfection Byproducts Rule (U.S. Environmental Protection Agency, 2006)?

This brings up the question of regulating five HAAs. There are nine bromine- and chlorine-containing HAAs, yet only five of them are regulated. When updating the Disinfection Byproducts Rule was first considered, occurrence data was available for only five of the



HAA species because analytical standards were not available for the other four. Accordingly, based on the limited occurrence data, a regulation encompassing only five of the HAA species was proposed. However, because laboratory research using synthesized analytical standards suggested that the other four HAA species might be important, especially in waters containing moderate concentrations of bromide (Cowman and Singer, 1996), the U.S.

Environmental Protection Agency included the option for measuring all nine HAA species as part of the Information Collection Rule (U.S. Environmental Protection Agency, 1996). Because of the expressed interest of

water quality researchers, commercial supply houses began to make analytical standards available for the remaining four HAAs. Approximately one-third of the nearly 500 utilities participating in the Information Collection Rule data-gathering exercise measured all nine of the HAA species and found that the four not slated to be regulated constituted a significant fraction (20 to 50 percent) of the overall HAA content of finished drinking

water. Nevertheless, despite this finding and the commercial availability of analytical standards for the other four HAA species, no changes were made to the Stage 1 Rule and it was finalized as initially proposed, regulating all four of the bromine- and chlorine-containing THM species but only five of the bromine- and chlorine-containing HAA species.

To make matters worse, the Stage 2 Rule (U.S. Environmental Protection Agency, 2006),

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which was finalized 8 years after the Stage 1 Rule, continues to regulate only five of the HAAs. This has led to a misrepresentation of public exposure to this class of DBPs, especially for consumers served by utilities

impacted by bromide in their raw waters. It has also led to confusion in interpreting DBP data. For example, for utilities experiencing seasonal variations in bromide levels, THM concentrations closely track HAA concentrations during times of the year when bromide concentrations in raw water are low. Conversely, when bromide concentrations are elevated, the two classes do not track each other in the same manner, and HAA concentrations appear



to be much lower. This apparent anomaly occurs because more bromine is incorporated into HAA species that are not a part of the five HAA species that are regulated. Because of this, HAA concentrations appear to experience a much wider variability than THM concentrations and tend to inversely track bromide levels in the raw water. Again, this leads to an underestimation of HAA occurrence and an underestimation of exposure to these byproducts. As people have heard me say before, regulating only five HAAs is neither sound science nor sound policy.

Accordingly, I call on all utilities to modify their monitoring programs to measure all nine bromine- and chlorine-containing HAA species. While they are only required to report the sum of the five regulated species, they will have a much better understanding of their system and the inter-relationships among source water quality, treatment practices, and DBP formation if all nine species are measured.

I would hope, in future versions of the DBP regulations (and there will most assuredly be future versions), that the U.S. Environmental Protection Agency will regulate all nine bromine- and chlorine-containing HAAs to accompany the regulation of all four bromine-

and chlorine-containing THMs. This would be the most prudent course of action for limiting public exposure to these two classes of DBPs.

Lastly, on this issue of shortcomings associated with the regulation of DBPs, it is time to regulate individual DBP species rather than class sums. For more than 25 years, we have avoided this. Back in 1979, there were insufficient health effects data to establish meaningful maximum contaminant levels for individual THM species. But since that time, a great deal of research has been conducted on the human health effects of individual THM and individual HAA species, as well as on other halogenated byproducts arising from the chlorination of drinking water. We have to get beyond regulating the class sums as has been done historically. For example, the World Health Organization has established different guideline values for each of the four THM species (World Health Organization, 2005). The guideline values are 300 micrograms per liter ( $\mu\text{g/L}$ ) for chloroform, 60  $\mu\text{g/L}$  for bromodichloromethane, 200  $\mu\text{g/L}$  for dibromochloromethane, and 100  $\mu\text{g/L}$  for bromoform. My intent here is not to recommend that these values should be the regulatory levels in the U.S., but simply to suggest that the species be





addressed individually. This is a policy that should be adopted by the U.S. Environmental Protection Agency the next time regulation of DBPs is considered.

A good example of the importance of regulations based on individual species is illustrated in Figures 1 and 2, which show the average distributions of THM and HAA species, respectively, for two different water systems that we have studied (Savitz et al., 2005).

While the two systems have very similar total THM and total HAA concentrations, Site 3 has a greater concentration of bromine-containing species than Site 1. If, indeed, the bromine-containing species are more harmful than their fully chlorinated counterparts, it is obvious that the consumers served by the Site 3 utility are at greater risk than those served by the utility at Site 1.

Extending this point further, recent research (Weinberg et al., 2002) has shown that other THM and HAA species are formed when water is chlorinated, namely iodinated species that arise from the oxidation of natural iodide in water. Research suggests that a number of these iodine-containing species are more hazardous than those containing only chlorine and bromine. Because the concentrations of

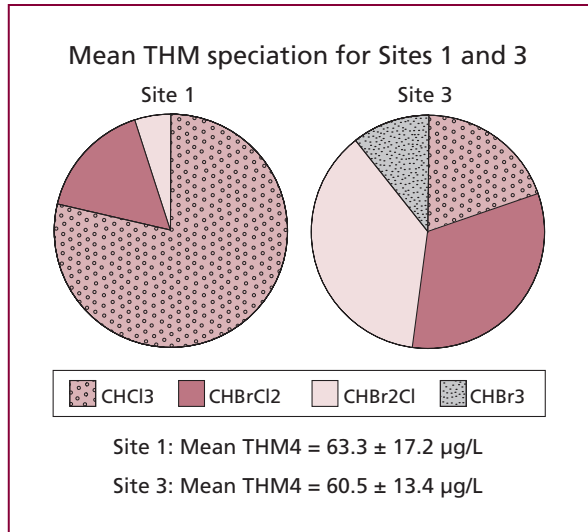


Figure 1. Speciation of THMs at two different water utilities with similar total THM concentrations.

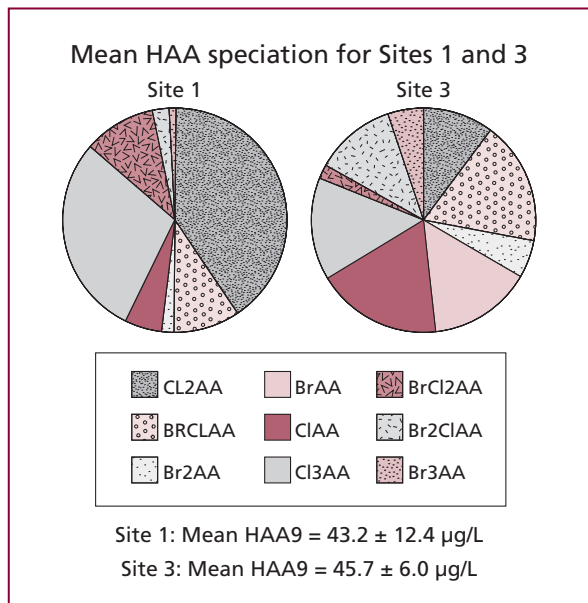



Figure 2. Speciation of HAAs at two different water utilities with similar total HAA concentrations.



these iodinated species in most waters are expected to be much lower than those containing only chlorine and bromine, the regulation of group sums, such as total THMs and total HAAs, is not likely to reflect the presence of these more harmful compounds. They need to be regulated separately, just as all of the other halogenated DBPs should be individually regulated in accordance with their relative health effects. Only then will we have a regulatory policy that is truly protective of public health.

### **Need for More Effective Management Strategies to Control DBPs**

Since the establishment of the first THM regulation in 1979, many water utilities have made major modifications to their treatment practices. These include:

- Moving the point of chlorination from a raw water application point to a location downstream of clarification and/or filtration.
- Enhanced coagulation for the removal of additional natural organic material.
- Use of alternative oxidants and primary disinfectants (such as ozone, chlorine dioxide, permanganate, ultraviolet

irradiation, and advanced oxidation processes) within the treatment plant in place of free chlorine.

- Use of alternative secondary or terminal disinfectants, notably combined chlorine, in the distribution system in place of free chlorine.

Some utilities have also adopted the use of granular activated carbon adsorption or the use of nanofiltration to remove natural organic materials that are the precursors with which chlorine reacts to produce DBPs. While each of these approaches has allowed utilities to control the production of THMs and HAAs and to comply with existing DBP regulations, they are not without their own problems.

For example, moving the point of chlorination has made it more difficult for utilities to oxidize and remove manganese from raw water and has led to nuisance aquatic growths in flocculation basins and clarifiers. Enhanced coagulation has led to the production of excess sludge and increased chemical costs associated with pH adjustment. Alternative oxidants and primary disinfectants create their own oxidation byproducts and DBPs: ozone produces bromate and biodegradable organic material that must be controlled, and chlorine



dioxide produces chlorite and chlorate. The use of monochloramine or combined chlorine as a terminal disinfectant in distribution systems can lead to biological nitrification problems and has been linked to the production of nitrosodimethylamine (NDMA) (Choi and Valentine, 2002) and elevated levels of lead (Edwards and Dudi, 2004) in tap water.

Approximately 40 percent of the utilities in the U.S. today use chloramines in their distribution systems. More are likely to adopt this practice with the implementation of the Stage 2 Disinfectants/Disinfection Byproducts Rule because the use of chloramines essentially leads to the cessation of THM and HAA formation in finished water. This allows all consumers in the service area to be exposed to the same level of these regulated DBPs and thereby receive equitable levels of protection. Additionally, chloramination is a relatively inexpensive process, which is easy to implement. For these reasons, many utilities in the U.S. switched over to chloramines as a preferred and inexpensive solution to the DBP

problem when THMs were first regulated in 1979. However, all systems using chloramines are subject to nitrification problems, and many have experienced such problems (Wilczak et al., 1996). More problems are on the way. Research has shown that NDMA, a proven carcinogen, is present at appreciably higher levels in systems using chloraminated water than in systems using free chlorine as their terminal disinfectant (Choi and Valentine,

2002). Additionally, recent research has shown that iodinated byproducts, such as iodomethanes and iodoacetic acids, are higher in distribution systems using chloramines than in systems using free chlorine

(Weinberg et al., 2002). There are plausible chemical explanations underlying both of these observations.

The bottom line is that, despite the attractiveness of chloramination as a DBP management strategy, it must be considered a temporary solution at best. More permanent solutions need to be sought. Such long-term solutions must rely on the management and control of natural organic material and bromide, the two

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principal precursors of DBPs, in our raw water supplies. This involves effective watershed protection and water resources management strategies. It involves controlling algal growth and the production of organic carbon precursors in our raw water sources by limiting nutrient discharges into bodies of water that become our raw water supplies. It involves creative solutions to minimizing saltwater intrusion into our raw water supplies because saltwater intrusion is a source of bromide.

If effective source-control management strategies for natural organic material and bromide can be implemented, or if greater amounts of natural organic material can be removed from raw water by more effective pretreatment, then downstream treatment will be cheaper, easier, and more effective. Coagulant dosage requirements will be reduced and less sludge will be generated if there is less dissolved organic carbon in raw water because, in most waters, it is the concentration of dissolved organic carbon that controls coagulant dosage requirements. Ozonation doses for effective oxidation and disinfection will be lowered if there is less dissolved organic carbon in raw water to exert an ozone demand and less bromate will be

formed if there is less bromide in raw water. Chlorine dioxide doses will be lowered if there is less dissolved organic carbon in raw water to consume chlorine dioxide and make chlorite. Powdered activated carbon doses and granular activated carbon usage rates for the control of taste and odor-causing organics and for the removal of synthetic organic compounds will be reduced if there is less dissolved organic carbon in raw water to compete with target trace organic pollutants for adsorption sites on activated carbon. Membrane fouling will be lowered and ultraviolet irradiation for microbial inactivation will be more effective if there is less dissolved organic carbon and ultraviolet-absorbing organics in raw water. And, of course, less chlorine will be required for disinfection and lower concentrations of all halogenated organic byproducts, not just THMs and HAAs, will be formed.

In adopting more creative and more long-lasting DBP management and control strategies, one more important point needs to be considered. In some cases, bromide control may be even more important than the control of natural organic material. Researchers have shown that the increased removal of natural organic material using enhanced coagulation,



granular activated carbon adsorption, and nanofiltration, while lowering the overall formation of THMs and HAAs, actually can result in an increase in some of the more brominated forms of these classes of compounds (Symons et al., 1993; Black et al., 1996); as noted, some of these bromine-containing compounds may be of greater health concern than their fully chlorinated counterparts.

Bromide control strategies may involve more energy-intensive

membrane processes, such as reverse osmosis.

Anion exchange, for the removal of both natural organic material and bromide, is a technology worth considering.

Aquifer storage and

recovery (Pyne et al., 1996), another creative management approach when properly employed, allows utilities to draw and treat excess amounts of surface water when the water is high in quality and low in bromide concentration, store the treated water in an underground aquifer, and then draw from the aquifer when raw water bromide concentrations are elevated.

In any case, utilities must accept that the ultimate solution to DBPs will be more expensive and will necessitate the use of more aggressive management and control strategies. Some of the more progressive utilities in the U.S. are already exploring – and some have even implemented – such practices. In the future, as we continue to learn even more about DBPs and their health effects, we are likely to see many more utilities moving in this direction.

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The 2006 Stage 2

Disinfectants/ Disinfection Byproducts Rule is not the end of the story.

### **Thank You**

In closing, I would first like to thank the National Water Research Institute,

the family of Athalie Richardson Irvine Clarke and Joan Irvine Smith, and the Clarke Prize Executive Committee for selecting me as the recipient of this year's Clarke Prize. I am honored to be included among the very distinguished group of scientists and engineers that are previous Clarke Prize winners.

There are many people that played a major role in allowing me to achieve what I have



over my professional career. It all starts with my mentor, Werner Stumm, who was my Ph.D. advisor at Harvard University. Werner taught me aquatic chemistry. He taught us all aquatic chemistry. Although he passed away in 1999, he continues to teach us aquatic chemistry through his writings, his textbooks, and the many students he mentored both directly and indirectly. It is noteworthy that four of the 13 Clarke Prize recipients are students of Professor Stumm's. Another two are their students, and another did a sabbatical leave at Harvard with Professor Stumm. His impact on the water quality field is unparalleled.

Charlie O'Melia taught me process engineering. I first met Charlie when I was a Ph.D. student at Harvard and he was doing a post-doctoral research leave with Werner Stumm. Charlie was responsible for bringing me to UNC as a colleague in 1973, an opportunity for which I am eternally grateful because it helped define my life for the next 33 years. Charlie is another great teacher who has served as a role model for so many.

Dan Okun, whose name I carry as a Distinguished Professor of Environmental Engineering at UNC, is another legend who casts a giant shadow. Dan has made a major

impact on the broader field of water supply and water resources management.

He exposed me to the bigger picture – the institutional aspects of the water resources engineering field – and he continues to be a conscience for all of us despite his retirement from UNC more than 25 years ago.

I thank Russ Christman, who was my first Department Chairman at UNC. Russ continued the vision of Dan Okun in building a truly multidisciplinary department of environmental sciences and engineering at UNC and was also instrumental in guiding my academic maturation and in fostering an understanding of the chemistry of natural organic material in water and the critical role it plays in water quality management.


I would like to thank my colleagues at UNC who make it such a fine university, a great place to work, teach, and learn, and a magnet for attracting some of the finest young people to become our graduate students. Along these lines, I am immensely proud of our students, what they have achieved while they were students and, even more so, what they have achieved in their professional and personal lives after leaving UNC.

I would like to thank my own students, the



ones who conducted their research with me – Masters’ and Ph.D. students alike. I take great pride in what we have accomplished. We have worked: at the fundamental level, understanding the chemical and physical principles of reactions in natural waters and in our treatment facilities; at the practical level, transforming what we have learned under controlled laboratory settings to real-world conditions; and at the policy level, exploring how our findings should inform regulatory policy and, ultimately, the protection of public

health. We have conducted our research in the laboratory and in the field. We have helped bridge the gap between theory and practice and have helped inform policy. I am grateful to have had the opportunity to work with and learn from so many of you.

And last, but by no means least, I would like to thank my wife of 41 years. Ellen, you have been at my side through it all, you have been my best friend and my confidant, you have been there when I needed you. Thanks for everything! 



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*The 2006 Clarke Prize Lecture, Disinfection Byproducts in Drinking Water: Additional Science and Policy Considerations in the Pursuit of Public Health Protection by Philip C. Singer, Ph.D., P.E., was first presented on Thursday, July 13, 2006, at the Thirteenth Annual Clarke Prize Award Ceremony and Lecture, held at Mission San Juan Capistrano in San Juan Capistrano, California.*

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

### National Water Research Institute

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The 2006 Clarke Prize Honoree

## PHILIP C. SINGER, PH.D., P.E.

*Daniel A. Okun Distinguished Professor of Environmental Engineering  
University of North Carolina at Chapel Hill*

**D**r. Philip C. Singer has devoted his 37-year career to increasing our knowledge of water chemistry and drinking water treatment. His research activities have spanned a broad range of water quality issues, from providing a fundamental understanding of the chemistry of ozone – allowing for the development of chemical oxidation processes as a safe, reliable, and cost-effective means to clean water – to understanding the formation and control of disinfection byproducts (DBPs) in drinking water. DBPs are formed when chlorine reacts with natural organic matter in water during treatment and, because several of them are considered human carcinogens, DBP formation has been one of the most challenging issues within the waterworks industry for the last 30 years.

Singer's pivotal work on DBPs has directly led to the development of water treatment and distribution practices to control DBP levels in drinking water



distributed to consumers. His research results were used by the U.S. Environmental Protection Agency in setting regulations for both trihalomethanes and haloacetic acids, the two major classes of DBPs, and in identifying coagulation as a best available technology to control DBPs. He has also taken the lead in linking environmental

engineering with epidemiological principles to provide an assessment of the effects of human exposure to DBPs in drinking water. One such effort is a 2005 publication that he co-authored, entitled *Drinking Water Disinfection By-Products and Pregnancy Loss*.

Singer received a Ph.D. in Environmental Sciences and Engineering from Harvard University, an M.S. in Sanitary Engineering from Northwestern University, and a Bachelor's Degree in Civil Engineering from The Cooper Union. 