Advancing the Science of Water: WRF and Research on Taste and Odor in Drinking Water

In addition to making sure the water at customers' taps is safe to drink, water providers must also meet customer expectations for the water's aesthetic characteristics—its taste, odor, and appearance. Although most contaminants that cause aesthetic problems in drinking water are not considered a threat to human health, unpleasant tastes and odors are the most common cause of customer complaints, and they often play a role when customers choose alternative supplies such as bottled water.

Because aesthetic characteristics are not usually related to public health, they are regulated by secondary standards—water quality goals that are not mandatory or enforced in most states. Nevertheless, customers who find the taste or smell of tap water disagreeable often assume the water is of poor quality and, therefore, unsafe to drink. Thus, water utilities need to be proactive in identifying and mitigating taste and odor episodes.

Taste and odor problems can stem from microbiological or chemical causes and can be triggered by conditions in source water, during treatment, or in distribution systems. For example, the presence of salts and metals such as iron, copper, manganese, or zinc can impart undesirable flavors. Blue-green algae and actinomycetes that grow in surface supplies produce compounds that cause earthy–musty odors. Some consumers object to the flavor of chlorine, and disinfection by-products formed when chlorine combines with naturally occurring organic matter can cause off-flavors.

"WRF has played the key role in advancing our understanding of taste and odor problems in drinking water," said Gary Burlingame, administrative scientist with Philadelphia Water Department's Bureau of Laboratory Services. "Water utilities often don't deal with this issue till it becomes a problem; then once it's gone, they stop dealing with it and it comes back again. Analyzing water samples for tastes and odors is time-consuming and expensive. Most utilities have to contract it out, and outside labs generally charge $200 to $400 per sample. So it's a struggle for utilities to look at this problem proactively. WRF takes us out of the day-to-day grind and allows us to think more creatively, be more progressive, and solve the long-term problems that keep plaguing us."

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WRF has been funding studies of drinking water tastes and odors for more than 20 years. Its fundamental contributions to the science of controlling tastes and odors include:

- Identifying the sources of common tastes and odors in drinking water.
- Adapting sensory techniques from the food and beverage industries to identify drinking water tastes and odors.
- Correlating sensory methods of identifying tastes and odors with results from analytical instruments.
- Refining taste and odor data collection methods and terminology, enabling water professionals across the globe to share their knowledge.
- Synthesizing state-of-the-art information on taste and odor causes and solutions.
- Comparing taste and odor changes in response to various control strategies applied in supply sources, during treatment, and in distribution systems.
- Creating a taste and odor wheel delineating eight distinctive types of odors and four tastes.
- Linking complaints about kerosene and cat urine odors with a utility's use of chlorine dioxide and the presence of new carpeting in customers' homes.
- Evaluating methods to control chlorine dioxide by-product residuals.
- Elucidating the role of various algal species in producing tastes and odors.
- Devising a bench-scale protocol to help utilities select appropriate powdered activated carbon brands, doses, and application points.
- Investigating consumer attitudes about tap water, bottled water, and point-of-use filtration devices and pinpointing people's reasons for choosing tap water alternatives.
- Producing a self-assessment tool to help utilities evaluate their preparedness to deal with taste and odor episodes.
- Providing guidance for communicating with utility staff and the public during and after taste and odor events.
- Recommending the use of early-warning signals to avert or minimize taste and odor episodes.

Identifying Compounds That Cause Tastes and Odors

WRF's first taste and odor project used both sensory methods and analytical instruments to identify compounds that produce tastes and odors in drinking water ("Taste and Odor in Drinking Water Supplies," Project 55, funded 1983, published 1989, order number 90542). Mel Suffet, with Drexel University at the time, directed the study in cooperation with Philadelphia Water Department, Philadelphia Suburban Water Company (now part of Aqua America, Inc.), and the French water utility Lyonnaise des Eaux (now part of Suez Environment).

"WRF funding allowed us to bring in chemists to help us with analytical techniques to isolate and describe the compounds that cause tastes and odors," said Robert Hoehn, professor emeritus of Civil and Environmental Engineering at Virginia Tech and a consultant with Black & Veatch. "Prior to that, we had no instruments except our noses, and we had no way to correlate what we smelled with any analytical profiles."

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The analytical techniques used in the study were closed loop stripping analysis (CLSA) coupled with gas chromatography (GC) and mass spectrometry (MS). The sensory technique, called flavor profile analysis (FPA), was adapted first by Metropolitan Water District of Southern California (MWDSC) from methods traditionally used in the food and beverage industries. FPA relies on trained panelists to analyze the characteristics and intensity of flavors in a water sample, and the technique is now included in *Standard Methods for the Examination of Water and Wastewater*. In addition to introducing drinking water professionals to these new tools, the research team determined correlations between FPA and GC–MS analysis and monitored taste and odor changes during conventional water treatment in the United States and ozonation at a French water treatment plant.

"This work was groundbreaking because it gave us methods for collecting data that could be compared across the world," said Burlingame. "It was also important in that it came up with terminology that helped us communicate with one another. Once we had methods of collecting reliable data and language that allowed us to understand what each other was saying, we discovered we were dealing with universal problems, whether they occurred in Philadelphia, California, or France, on a customer's premises, in a reservoir, or at a treatment plant."

Synthesizing State-of-the-Art Information

The first publication resulting from an WRF taste and odor project was a 300-page manual summarizing current American and European technology to detect and remove taste- and odor-producing compounds in drinking water ("Identification and Treatment of Tastes and Odors in Drinking Water," Project 118, funded 1985, published 1987, order number 90518). Another cooperative effort between WRF and Lyonnaise des Eaux, the project was led by Joel Malleviallle.

One chapter of the book reviewed the results of several surveys of customer opinions about drinking water quality. Among these surveys was WRF's nationwide 1985 study concluding that taste and odor were the two most important criteria in determining consumer attitudes about drinking water. Another chapter detailed the sources of tastes and odors in drinking water, from inorganic salts and dissolved gases to natural and anthropogenic organic chemicals, industrial products, and biological sources.

Subsequent chapters covered techniques for classifying and analyzing taste and odor compounds. As a starting point for standardizing reference material in the water supply profession, the research team proposed a flavor wheel patterned after those used in various food and beverage industries, and they recommended eight groups of odor descriptors.

In addition to outlining FPA's advantages for describing the characteristics and intensities of tastes and odors, the book presented methods for integrating the results of sensory and chemical analyses. Finally, it described the relative advantages of various treatment technologies for controlling tastes and odors.

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A follow-up manual, also produced by WRF and Lyonnaise des Eaux, was published eight years later. This book focused on various treatment processes used by water utilities in North America and Europe and examined the effects of these processes on tastes and odors ("Advances in Taste and Odor Treatment and Control," Project 629, funded 1990, published 1995, order number 90610). A network of volunteer authors from both sides of the Atlantic provided an international perspective on the range of treatment alternatives available.

The book began with monitoring and treatment approaches used to alleviate taste and odor problems in both surface water and groundwater supplies. Subsequent chapters discussed unit processes that can affect a water supply's sensory attributes inside the treatment plant, including chlorination, chloramination, chlorine dioxide oxidation, ozonation, and the addition of potassium permanganate. Another chapter described the impact of distribution system materials and operations on tastes and odors and suggested potential solutions.

The book included an updated version of the taste and odor wheel proposed in the earlier report. The new wheel, which delineated eight types of odors and four tastes, was designed to help utilities define their specific chronic and episodic taste and odor problems, as well as to communicate with consumers about taste and odor concerns.

These handbooks are the two most frequently referenced books dealing with tastes and odors in drinking water.

Tastes and Odors Associated With Chlorine Dioxide

Attempting to minimize the formation of certain disinfection by-products, a number of U.S. water utilities began using chlorine dioxide for oxidation and disinfection and then adding chlorine or chloramines to provide a residual disinfectant in the distribution system. But this treatment change also gave rise to an unanticipated consequence— complaints about offensive odors. Customers in various locations along utility distribution systems reported that their water smelled like chlorine, kerosene, or cat urine.

Hoehn wanted to solve this problem. With WRF funding, he and his colleague Andrea Dietrich pursued a three-part research plan consisting of field studies, a survey of water utilities using chlorine dioxide, and an investigation of treatment processes to reduce the tastes and odors that were prompting customer complaints ("Taste-and-Odor Problems Associated With Chlorine Dioxide," Project 405, funded 1988, published 1991, order number 90589).

During the field studies, the research team visited utilities that were experiencing taste and odor episodes associated with chlorine dioxide and analyzed samples for organic and inorganic chemicals that might be causing the problem. The team determined that the organic compounds responsible for kerosene and cat urine odors were not detectable in water leaving the treatment plant, entering customer service connections from the distribution system, or in residential plumbing. They also found that none of the organic chemicals identified in homes with odor problems could be associated exclusively with the kerosene and cat urine odors.

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"Serendipitously, someone at the New York State Department of Health heard about our investigation and called to ask if we had heard about the possibility that new carpeting might be involved," Hoehn recalled. "I snickered and said I hadn't seen any evidence to support that idea. Then the person told me that 50 utilities in the state of New York had found new carpeting in homes where kerosene odors had been reported. Sure enough, I was able to reproduce that odor in my office simply by pouring chlorine dioxide into a beaker and leaving scraps of carpet in the office overnight. Then I went to a local church that had just installed new carpeting and generated the odor there."

As it turned out, the odor problems were indeed correlated with the presence of new carpeting in the customers' homes rather than the water quality characteristics of untreated or finished water.

"We linked the regeneration of chlorine dioxide—after it had been applied in the treatment plant and after the water had been chlorinated—to the kerosene and cat urine odors," Hoehn said. "Working with a utility in Lexington, Kentucky, we found trace amounts of chlorine dioxide in the water. Some people thought this was not enough to cause a problem, but we discovered in a subsequent study that less than a tenth of a milligram per liter of chlorine dioxide will be scrubbed out into the air and react with airborne compounds to create these odors."

The survey of utilities using chlorine dioxide yielded 35 responses. With this information, Hoehn and Dietrich created a database on water treatment practices, water quality, and odor problems associated with this chemical. Because chlorite, a by-product of chlorine dioxide disinfection, had been implicated as a cause of tastes and odors, the researchers also conducted laboratory-scale tests to determine the efficacy of powdered activated carbon (PAC) at reducing chlorite concentrations. They found that floc-enmeshed PAC was more effective at removing chlorite than freely suspended PAC.

"This project is an example of a success story in which an WRF project wrapped things together and solved a problem for the drinking water community," said Burlingame. "The study addressed this issue from cause to solution."

Elucidating the Role of Algae in Producing Odors

The next task tackled by the Virginia Tech team was an WRF study on the contributions of algae to taste and odor episodes. Using both sensory and GC–MS analyses, the researchers investigated the odors and organic chemicals produced throughout the life cycles of eight types of algae ("Identification and Control of Odorous Algal Metabolites," Project 716, funded 1991, published 1996, order number 90682).

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Results showed that younger algal cultures with lower cell densities generally released less intense odors and, in some cases, different odors than older cultures. Some odor-causing compounds were retained within the cells, whereas others were detected outside the cells. Using continuous liquid–liquid extraction combined with GC–MS, the researchers identified trace concentrations of a broad range of organic chemicals both inside and outside the cells, but they had to rely on FPA to detect odors below the detection limits of the analytical instruments.

Individual algal species produced diverse effects. For example, blue-green algae released geosmin, which produced odors described as "sweet–earthy–corn–grassy." Low phosphorus and low light conditions resulted in lower population densities and thus lower geosmin concentrations. Young cultures of *Microcystis aeruginosa* generated odors described as "sweet–melon–grassy–corn," but older cultures of this species created "oily– fishy" and "rancid–fishy" odors. *Oscillatoria* species produced 2-methylisoborneol (MIB) and linolenic acid but no detectable geosmin. The MIB caused an earthy–musty smell, and the linolenic acid produced a slight "sweet–melon–corn–grassy" odor. Other species tested produced odors as diverse as "cucumber," "fishy," "meadowlike," "rancid," and "fruity–sweet–floral."

The researchers advised that minimizing algae-induced odors requires water utilities to determine the odor's source (the specific alga and compound responsible) and the environmental factors that affect algal growth. They also recommended monitoring programs to help utilities control responsible organisms before they reach or exceed critical population density.

Removing Geosmin and MIB with PAC

By the early 1990s, many water utilities were applying PAC to mitigate taste and odor problems, particularly the earthy–musty odors attributed to geosmin and MIB. But according to Burlingame, "they were using different brands of carbon and feeding it all over the plant, so they weren't getting their money's worth or the removals they needed." Then a pivotal WRF study conducted by Issam Najm (with MWH Americas, Inc., at the time), devised a systematic approach to maximizing the effectiveness of PAC treatment ("Optimization of Powdered Activated Carbon Application for Geosmin and MIB Removal," Project 909, funded 1993, published 2000, order number 90782).

The study consisted of four steps: conducting a survey of water treatment plants using PAC for taste and odor control; developing a protocol for evaluating PAC at bench scale; verifying this protocol against full-scale results; and examining various influences on PAC performance, including initial PAC concentration, contact time, and application conditions. Four utilities in the United States and Canada used the bench-scale protocol to evaluate differences in PAC brands, application points, and feed methods. Different types of PAC performed differently in the four water supplies, and the bench-scale findings effectively mimicked results from the full-scale plants.

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Project results demonstrated that for the range of PAC concentrations tested, the initial concentrations of geosmin and MIB did not affect their removal percentages. PAC was most effective at removing odors when it was added prior to coagulation, and greater removals were achieved with longer precoagulation contact times. Adding chlorine or potassium permanganate reduced the removal of odor-producing compounds.

Najm advised utilities that use PAC for taste and odor control to develop a site-specific, bench-scale protocol to guide them in evaluating PAC brands, doses, and performance. He also recommended that utilities add PAC as early in the treatment process as practical.

Tastes and Odors Originating in Distribution Systems

As water suppliers learned more about how their treatment decisions affect tastes and odors, they began to focus more attention on taste and odor problems that begin in distribution systems. Hoehn compared this phenomenon with an arcade game. "I tell my students that treating drinking water is a lot like playing Whac-a-Mole," he said. "You solve one problem and two more pop up."

To further explore the problem of tastes and odors produced in pipe networks, WRF co-sponsored a project with UK Water Industry Research Limited ("Distribution Generated Taste-and-Odor Phenomena," Project 365, funded 1996, published 2002, order number 90897). The project team included researchers from Agbar Water in Barcelona, Spain. Results implicated several factors as causes of distribution system tastes and odors, including biological activity, disinfectants and their by-products, distribution system materials, and the practice of blending chlorinated and chloraminated supplies.

The research team determined descriptors and odor threshold concentrations for numerous chemicals found in low concentrations in distribution systems. They ascertained that disinfectants partially controlled or masked tastes and odors emanating from biological causes but that as the disinfectant decayed, the masking effect diminished, resulting in the appearance of earthy or musty odors. The researchers also designed an investigative procedure to help utilities respond efficiently to customer complaints about tastes and odors.

The project, led by Djanette Khiari (with Metropolitan Water District of Southern California at the time), produced a distribution system taste and odor wheel correlating sensory descriptors with causative agents specifically associated with distribution system tastes and odors. An accompanying table listed potential corrective actions to prevent or eliminate taste and odor episodes. These actions included source water management practices to deal with taste and odor precursors, treatment process changes, and modifications in distribution system operations.

Customer Perceptions of Taste and Odors

To help water utilities deal with public attitudes about tastes and odors, WRF funded two companion projects aimed at pinpointing customer opinions about tap water and its alternatives. Gil Crozes, manager of the research group at Carollo Engineers, spearheaded both studies.

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The first of these projects used a survey of 12 U.S. markets to assess consumer satisfaction with tap water quality, to investigate demographic trends in the use of alternatives to tap water, and to identify factors that prompt consumers to choose bottled water and point-of-use/point-of entry filtration devices ("Consumer Perceptions of Tap Water, Bottled Water, and Filtration Devices," Project 2638, funded 1999, published 2003, order number 90944F).

"This study broadened the scope of taste and odor research by going beyond the analytical realm to try to understand why customers make the decisions they do," said Burlingame.

The survey results, comprising almost 2,400 responses to more than 50 questions, formed a database designed to help utility staff create more effective customer education and public relations programs. The findings indicated that utility managers tend to overestimate customer satisfaction and underestimate the degree of importance consumers place on tap water's safety. Survey respondents who used filtration devices cited safety as the primary reason. People chose bottled water because of taste as well as perceived safety and healthiness. The use of alternatives to tap water depended greatly on geographic location—a usage rate of 20 percent in the Midwest compared with 80 percent on the West Coast at the time of this study.

The companion project focused on customer attitudes about the chlorinous flavor of tap water ("Public Perception of Tap Water Chlorinous Flavor," Project 2639, funded 1999, published 2004, order number 90980F).

"This was timely research on the background flavor of tap water as utilities considered how to optimize the use of secondary disinfectants to control disinfection by-products," said Burlingame. "Chlorinous flavor is what makes tap water different from any other water source. This study finally got around to saying that water utilities know how to deal with off-flavors, but even if we kept all of these out of the water, we would still have the background flavor caused by the chlorine residual."

Results of this study showed that consumers generally had a negative opinion of chlorinous tastes and odors in their drinking water, both in terms of aesthetics and safety. Their attitudes toward off-flavors such as earth–musty, metallic, or plastic odors were even more negative. The project report, which includes a CD-ROM summarizing project data, discussed how utilities can improve customer satisfaction with respect to chlorinous flavors in drinking water.

Practical Methods for Identifying Tastes and Odors

Because many water utilities lack sufficient personnel and budget to train designated staff members in FPA, the need for more practical sensory methods to control tastes and odors became apparent. An WRF project enabled Dietrich, Hoehn, and Burlingame to develop alternative methods that were akin to a sensory method utilities had used before MWDSC researchers developed the FPA ("Practical Taste-and-Odor Methods for Routine Operations: Decision Tree," Project 467, funded 1997, published 2004, order number 91019).

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"For years utilities used the threshold odor test to rate the intensity of odors in their source water as well as the effectiveness of their treatment methods for taste and odor control," Hoehn explained. "But so much variability crept into that method—one operator would train another, perpetuating techniques that deviated from the standard method— that researchers found little correlation between the threshold odor number assigned to a given odor in a water supply and the concentrations of geosmin and MIB measured in that supply. FPA was a better method because it came up with a profile of odors that included intensity levels for various descriptors. Nevertheless, smaller water systems stuck with the threshold odor number because they couldn't afford to dedicate the time and personnel required for FPA training."

Dietrich's project produced three new sensory methods that could be used in routine water utility operations at the treatment plant, in the field, or in the quality control lab. The new methods were: (1) the attribute rating test, which teaches people to recognize and rate the intensity of earthy odors like that caused by geosmin; (2) the triangle method, which allows an analyst to compare distribution system odors with odors in a control sample representing the utility's typical or ideal finished water; and (3) the 2-of-5 odor test, a forced-choice method requiring an analyst to sort five samples into a group of two and a group of three based on their odor. Work on the 2-of-5 test included researchers in South Korea.

"The 2-of-5 test decreases the likelihood that someone could pick out the water that's different by chance," Hoehn said.

All three new methods were simple and inexpensive, minimized subjectivity, and required only an hour or two of training and less time to perform. The researchers also created a scenario-based decision tree to help a water utility select the most appropriate method for its system.

Self-Assessment Techniques for Utilities

A utility that is prepared to deal with taste and odor events can act more quickly to avert or manage them, and handling such episodes successfully requires a communication plan as well as technical solutions. A recent WRF project offered water utilities additional planning tools for tackling taste and odor problems, including tips for communicating with staff members and the public ("Water Utility Self-Assessment for the Management of Aesthetic Issues," Project 2777, funded 2001, published 2004, order number 90978F). Mike McGuire and his colleagues at McGuire/Malcolm Pirnie conducted the study, and 41 North American utilities participated.

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An online survey comprising part of the project revealed that many utilities do not train staff members to identify or prevent taste and odor events. In response to this finding, the project team produced two new tools to help utilities deal with taste and odor episodes. A self-assessment tool was designed to help utilities evaluate their level of preparedness for identifying and controlling taste and odor problems. A decision-tree tool offered guidance on managing all aspects of a taste and odor episode, including identification, control, and communication. An interactive CD walks users through the steps involved.

"This project, like Dietrich's study, has worldwide applicability, and its results could be particularly helpful to small and medium-size systems," Burlingame said. "But it illustrates one of WRF's challenges—getting user-oriented results out to people who could benefit the most."

Early-Warning Systems

By the time customers begin to complain about unpleasant tastes or odors, the cause of the problem is likely to have intensified. Because of the narrow window of opportunity between detection and full-blown taste and odor episodes, a utility's best defense is to anticipate such problems and control them at the source.

Another recent WRF project, conducted by the Metropolitan Water District of Southern California, came up with an early-warning system for utilities that rely on surface water supplies ("Early Warning and Management of Surface Water Taste-and-Odor Events," Project 2614, funded 1999, published 2006, order number 91102). The early-warning strategy consists primarily of preventive measures that limit the likelihood of taste and odor events—for example, monitoring for precursor conditions such as the presence of algal metabolites with sensory properties. (This approach, of course, requires a lab that can provide accurate results within a few hours.)

The project report synthesized the experience of numerous North American utilities at monitoring and managing source water taste and odor events for more than 25 years. The utilities ranged from simple systems with a single supply and one treatment plant to complex systems with multiple sources, extensive conveyance and storage systems, and several plants.

Direct measurements of MIB and geosmin were deemed the best predictor of taste and odor episodes. The research team recommended that utilities design monitoring programs to detect increases in these compounds at key locations and at low concentrations. When concentrations rise, the utility should quickly identify the cause, the researchers advised. Blending or withdrawing selected sources were among the management strategies proposed. If chemical treatment is necessary, it should be targeted specifically at the responsible compounds and implemented as rapidly as possible, according to the report.

The researchers advocated the use of FPA to anticipate consumer complaints and CLSA or solid-phase microextraction to measure MIB and geosmin. They also emphasized the importance of a timely, responsive communications program to address consumer concerns and rebuild confidence after a taste and odor event.

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Future Challenges and Research Needs

Asked about future research needs related to taste and odor control, Burlingame catalogued the advances WRF research has achieved so far and added, "What remains is to more fully understand the taste and odor removal benefits of advanced treatment processes, ozonation and biological filters, and disinfection with ultraviolet light in the context of a changing regulatory agenda. We also need to stay on top of the potential effects of new developments such as new materials."

As for other challenges in the taste and odor field, Burlingame said, "Our biggest challenge is disseminating the information we have to more people—particularly to small and medium-size systems that could use these data to improve their water supplies."

Hoehn expressed a similar view. "The challenge is getting utilities to use the information that's available," he said. "It's hard to get money for operators to attend workshops these days. We need a resurgence of interest in offering taste and odor workshops through the AWWA sections and in providing money to train the current crop of operators to use the tools we have."

Climate change poses another challenge, according to Burlingame. "As climate conditions change, whether we get more droughts or more flooding because of rains, we'll see aesthetic effects on drinking water. Warmer weather and dryer conditions will promote more serious algal blooms, which will lead to more geosmin and MIB problems," he said.

"Detection levels for geosmin and MIB in water are so low—some of us can smell these compounds at concentrations of 5 nanograms/litre—that many treatment methods (PAC, for example) can't remove them to that low level," Burlingame continued. "If we want higher-quality water than we have today, we'll have to find treatment methods that achieve this level of removal at an affordable cost and that take into account all the other water quality needs involved in treatment, or we'll have to figure out how to control the algae in source water. Because these problems are related to natural conditions, we may always need treatment to keep tastes and odors below threshold levels."

Noting that other treatment processes in addition to PAC can remove tastes and odors, Burlingame cited "advanced oxidation processes and ozone with biologically active filters, in which the microorganisms consume the geosmin and MIB." But he added that "these processes are more expensive and a little more difficult to operate, and we haven't fully elucidated how they fit into the larger scheme of controlling disinfection by-product formation and removing *Cryptosporidium*."

Even apart from climate change, Burlingame noted, taste and odor control will become more important worldwide. "As safe water supplies become available in places where drinking water hasn't been available, much less safe, communities will demand aesthetically acceptable supplies," he said. "As this comes about, WRF will be able to provide the answers, but we can't let the data we've collected just end up in some file or on some library shelf. We need to make sure people across the globe know that all this work has been done."

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Applying WRF Research Data

During the more than two decades in which WRF has been sponsoring taste and odor research, numerous water providers in North America and elsewhere have successfully applied its findings. One of Burlingame's favorite examples is SABESP, the water utility in Sao Paulo, Brazil.

"This utility's organic chemists wanted to learn more about taste and odor control, so they came to Philadelphia to see first-hand how we were analyzing taste and odor samples," Burlingame said. "They also took some of the training on flavor profile analysis that we offered at AWWA conferences. Then they went back to Brazil and created a first-rate sensory and chemical analysis lab that became recognized for its expertise. They have our taste and odor wheel posted on the laboratory wall."

"Utilities have benefited greatly from WRF's taste and odor research," said Hoehn. "They've used the results of WRF studies to identify the causes of taste and odor problems and to determine which mitigation processes worked and which didn't. They're not flying blind anymore. Prior to this, much of our success in controlling tastes and odors was based on anecdotal information rather than hard data. WRF research provided the instrumentation, analytical techniques, and treatment strategies required to put numbers where before there were only stories."

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