Advancing the Science of Water®

Advancing the Science of Water: AwwaRF and Distribution System Water Quality

People used to assume that if water entering a distribution system was of high quality, its quality would still be good at the tap. But water suppliers now recognize that water quality can deteriorate, sometimes substantially, even in distributions systems with integrity. Today's water providers understand that distribution systems are not inert pipe networks but biological and chemical reactors in which complex interactions and effects occur.

In addition to source water characteristics and treatment regimens, the principal factors that affect distribution system water quality are the condition of system components (including age and material), hydraulic considerations (including pressure, flow rate, and residence time), physical and chemical conditions that influence corrosion (including the secondary effects of corrosion control measures), and treated water characteristics (including pH, biostability, and the concentration of residual disinfectant).

"It's hard to separate water quality issues from infrastructure and hydraulic issues because they are intimately related," said Mark LeChevallier, director of innovation and environmental stewardship at American Water. "Compartmentalizing these issues is a little dangerous because a complete picture is necessary to understand distribution system water quality."

AwwaRF sponsored its first study of distribution system water quality in 1984. Over the ensuing 22 years, it has supported more than 100 research projects related to this topic with funds totaling almost $60 million. Though many of the early projects focused on fairly narrow biological and chemical concerns, recent studies have taken a broader view, examining the interconnections among various influences on the quality of water traveling through distribution networks.

AwwaRF's fundamental contributions to our understanding of the complexities of distribution system water quality include:

- Demonstrating that microorganisms growing on distribution system pipe walls can be controlled by improving distribution system disinfection, minimizing bacterial nutrients in treated water supplies, and preventing pipe corrosion.
- Observing that chloramines (disinfectants produced by mixing chlorine and ammonia) can be more effective than free chlorine at mitigating some bacterial regrowth problems.

- Contributing to the concept that primary and secondary disinfectants act by different mechanisms.
- Determining that pipe materials subject to corrosion are more likely to support the growth of coliform bacteria even when a disinfectant residual is maintained.
- Cataloging field conditions that correlate with coliform regrowth, including warm temperatures, infrequent distribution system flushing, and storing treated water in multiple storage tanks or uncovered reservoirs.
- Documenting treatment practices correlated with coliform regrowth, including use of free chlorine rather than chloramines as a residual disinfectant, lack of filtration, lack of corrosion control, and use of ozone without biologically active filters.
- Showing that monochloramine decay increases as pH and ammonia concentrations decrease.
- Indicating that nitrification episodes (caused by the release of ammonia during chloramine decomposition) can be reduced with better removal of chloramine-demanding natural organic matter.
- Discovering that enhanced coagulation is more effective than conventional coagulation at delaying the onset of nitrification.
- Identifying the most important water quality parameters related to lead solubility—pH, alkalinity, dissolved inorganic carbonate (the sum of all inorganic carbonate species), and orthophosphate concentrations.
- Providing guidelines for reducing the extent and severity of secondary effects caused by corrosion control measures, including designing utility-specific corrosion control programs and ensuring the stability of water in the distribution system.
- Recommending improvements in the design and operation of water storage tanks and reservoirs, including inspection procedures, turnover rates, and cleaning schedules.
- Establishing the value of using computer models to address myriad distribution system water quality issues, including simulating the water quality effects associated with chloramine decay and nitrification, simulating mixing behavior in storage facilities, and identifying locations with the longest hydraulic detention times.
- Verifying that transient variations in distribution system water pressure can allow contaminants outside the pipe to intrude into mains through leaks or orifices and that intruded water is carried downstream from the leakage point.
- Correlating pressure transients with power outages or pump shutdowns.
- Delineating the essential elements of a distribution system optimization plan, including distribution system water quality goals, a monitoring plan, biofilm control strategies, programs for managing finished water storage facilities and dead-ends, and a unidirectional flushing program.
- Encouraging water suppliers to develop standard operating procedures to facilitate communication among the multiple utility departments responsible for maintaining distribution system water quality.

Despite inextricable links among the factors affecting water quality in distribution systems, the easiest way to describe AwwaRF's contributions to this wide-ranging field is to divide its research into categories. Its most significant studies of distribution system water quality are discussed in this document under seven subtopics: biofilms; disinfectant residuals and decay; lead, copper, and corrosion; modeling; monitoring and sampling; pressure transients and intrusion; and water quality maintenance and operations.

Biofilms

Biofilms—layers of microorganisms bound by a matrix of organic polymers and attached to pipe walls—can degrade distribution system water quality in numerous ways. They can host pathogenic organisms, deplete disinfectant residuals, accelerate corrosion, and contribute to aesthetic problems such as color or disagreeable tastes and odors. Water supplies containing high concentrations of naturally occurring organic carbon support the growth of biofilms by providing nutrients for these microbes. Thus, controlling bacterial regrowth in distribution systems points to two key strategies—improving distribution system disinfection and minimizing bacterial nutrients in treated water supplies.

AwwaRF began funding research on biofilm growth in the mid-1980s. An early LeChevallier study examined the influence of biofilms and biological activity on water quality deterioration in distribution systems ("Assessing and Controlling Bacterial Regrowth in Distribution Systems," Project 309, funded 1987, published 1990, order number 90567).

LeChevallier and his research team studied biofilm disinfection in a model distribution system and evaluated the role of bacterial nutrients in coliform regrowth. Their results showed that disinfection of distribution system biofilms requires considering complex interactions among various pipe materials, disinfectant species, and microbial populations. The researchers concluded that simply maintaining a disinfectant residual in a water column was not sufficient if the biocide was unable to penetrate inactive bacteria in the biofilm. They also demonstrated that chloramine residuals had some advantages over free chlorine residuals in mitigating biofilm problems.

"At this point, the idea was that chlorine was a more powerful disinfectant than chloramines," said LeChevallier. "Some water suppliers were switching to chloramines because of the Disinfectants/Disinfection By-products [D/DBP] Rule, crossing their fingers because they were changing to a weaker disinfectant. They were pleasantly surprised when they didn't experience increased bacterial problems in the distribution system. In fact, they had fewer bacterial problems. This is when we further developed the concept of primary and secondary disinfection. In the treatment plant, you want a strong oxidant to rapidly kill the microorganisms. But in the distribution system, speed isn't as important as the disinfectant's ability to get at the bacteria in their biofilm environment. In some circumstances, chloramines were more effective at this than fast-reacting free chlorine. This brought about an evolution in our understanding of distribution system disinfection."

A subsequent AwwaRF project described various factors that influence the growth of microorganisms—particularly coliform bacteria—in distribution systems. These factors include pipe material, the concentration of assimilable organic carbon (AOC), disinfectant concentration, and hydraulic residence time. The researchers also identified field conditions that correlated with regrowth. Results of the study ("Factors Limiting Microbial Growth in Distribution Systems," Project 704, funded 1991) were published in 1996 as two reports: one on laboratory and pilot-scale experiments written by Anne Camper of Montana State University (order number 90708) and the other on full-scale experiments written by LeChevallier (order number 90709).

Laboratory studies showed that the type of material on which biofilms were grown was critical. More coliforms attached to mild steel than to polycarbonate materials, and pipe materials subject to corrosion were more likely to support coliform bacteria even when a disinfectant residual was maintained. "The research on iron pipe showed that corrosion interfered with the disinfectant's ability to get to the biofilms," explained LeChevallier.

The researchers used two types of pilot-scale systems—four-pipe annular reactors and a five-segment pipe loop. Results from both types of reactors were reproducible and qualitatively similar, but the annular reactors were less expensive to build and operate, easier to operate and sample, and provided higher numbers of organisms under the same conditions as the pipe loop.

According to the first project report, the laboratory and pilot experiments demonstrated that coliforms can colonize clean surfaces or become incorporated into established biofilms. Coliform numbers increased with (1) elevated organic carbon concentrations and short hydraulic residence times; (2) corrodible surfaces; and (3) the presence of a disinfectant residual when the organic carbon concentration was high. The researchers suggested that utilities could reduce regrowth potential by minimizing the concentration of organic carbon in the water and the amount of iron pipe in the distribution network.

The project's second report detailed the results of an 18-month survey of 31 North American water systems. Culminating in a comprehensive list of factors that contribute to coliform regrowth, the survey tracked chemical, physical, operational, and engineering parameters. Conditions associated with positive coliform samples included temperatures above 15° Centigrade, use of free chlorine rather than chloramines as a residual disinfectant, elevated AOC concentrations (especially in free chlorinated systems), lack of filtration, lack of corrosion control, use of ozone without biological treatment, infrequent distribution system flushing, large numbers of storage tanks, and storage of treated water in uncovered reservoirs. The researchers advised drinking water providers to consider all of these parameters—as well as their interactions—in devising solutions to regrowth problems.

"By the mid-1990s, we had a handle on most of the issues related to biofilms and biofilm control—so we could optimize disinfection, maintain a disinfectant residual, reduce AOC by adding activated carbon or implementing watershed control measures, and focus on corrosion control in the distribution system," said LeChevallier. "AwwaRF funded all this work. Thanks to this research, it's rare for any of our company's systems to have persistent coliform problems. Coliform regrowth resulting from biofilm problems is mostly gone."

Disinfectant Residuals and Decay

Research on disinfectant residuals has focused on the interaction of pipe surfaces with disinfectants, disinfectant decay, and DBP formation. "We knew how the disinfectants reacted with water samples, so we could predict DBP formation potential, but we needed to know how the disinfectants interact with DBPs formed on pipe surfaces," said LeChevallier. "The key was deriving some kind of reaction coefficient that we could put into models."

As chloramines were used more widely to achieve the dual objectives of providing disinfection and minimizing DBP formation, understanding their behavior in distribution systems became more critical. Chloramines are relatively unstable compounds, and their decay dynamics affect and are affected by water quality characteristics.

In an AwwaRF study of chloramine decomposition, Richard Valentine of the University of Iowa described the influence of water quality parameters on chloramine decomposition rates, compared decay rates in actual distribution systems with rates in model systems, and characterized chloramine decomposition products ("Chloramine Decomposition in Distribution System and Model Waters," Project 937, funded 1993, published 1998, order number 90721). Results showed that the rate of monochloramine decay increased as pH and ammonia concentrations decreased.

Valentine also produced two models of chloramine loss in drinking water. The more sophisticated model elucidates the reactions monochloramine undergoes as it decays. The simplified model can be used to determine the theoretical stability of monochloramine in a given finished water supply.

One consequence of chloramine decomposition is the release of ammonia, which can be oxidized to nitrite and ultimately to nitrate. This process, known as nitrification, is facilitated by ammonia oxidizing bacteria (AOB), which use the ammonia as an energy source. These bacteria are commonly found in drinking water systems, and nitrification occurs when conditions suddenly allow their numbers to rise. Nitrification can significantly diminish water quality and can cause violations of coliform, disinfectant residual, and nitrite limits.

Greg Harrington of the University of Wisconsin studied the influence of ammonia release on the growth of AOB and evaluated treatment methods to reduce the frequency of nitrification in distribution systems ("Ammonia From Chloramine Decay: Effects on Distribution System Nitrification," Project 553, funded 1997, published 2003, order number 90949). Harrington also produced a model that simulates the water quality effects associated with chloramine decay and nitrification.

For the water tested, pretreatment with enhanced coagulation proved more effective at delaying the onset of nitrification than conventional coagulation. These results suggested that nitrification episodes would be less frequent in utilities that improved the removal of chloramine-demanding natural organic matter.

Lead, Copper, and Corrosion

At the same time AwwaRF was supporting studies of the effects of biological growth and disinfectant decay in distribution systems, it was also funding research on the impact of metals released from deteriorating pipe materials.

The first of these was a project designed to help utilities of all sizes deal with the problem of lead in drinking water. Led by Gregg Kirmeyer, a vice-president of the consulting firm HDR/EES, Inc., this project provided guidelines for controlling lead leaching from distribution system components and for monitoring the effectiveness of lead control programs ("Lead Control Strategies," Project 406, funded 1988, published 1990, order number 90559). The research team also designed and tested a prototype pipe-loop system for evaluating lead concentrations at customer taps.

The manual produced at the end of this project examined the theoretical and practical aspects of controlling lead leaching through chemical means. The authors cautioned suppliers to select chemical treatments that are appropriate for specific water quality characteristics and to examine the potential side effects these treatments might have on other water quality parameters or treatment processes. The most significant water quality parameters related to lead solubility were pH, alkalinity, dissolved inorganic carbonate (the sum of all inorganic carbonate species), and orthophosphate concentrations. The authors especially emphasized the importance of pH adjustment, which can affect many other parameters and processes, including disinfection efficiency, coagulation, precipitation of iron and manganese, DBP formation, and scaling.

"This work, which we did with the Illinois State Water Survey, anticipated the Lead and Copper Rule," said Kirmeyer. "We developed lead control strategies that enabled utilities to be ready to treat their water supplies to meet the corrosion control requirements of the regulation. By funding this project, AwwaRF was ahead of the game, giving utilities a tool to meet the standards in this rule." The regulation was promulgated in June 1991.

"Hundreds of utilities across the country have used the lead control strategies report," Kirmeyer said. "These utilities constructed and operated pipe loops in order to select the best corrosion treatments for their systems. Dozens of large utilities used the results of this study to convince state agencies that they had optimized their treatment processes. Then, what those utilities learned trickled down to smaller utilities."

When some utilities experienced secondary water quality effects after implementing treatment to reduce lead and copper concentrations, AwwaRF funded another Kirmeyer study to investigate this problem ("Distribution System Water Quality Changes

Following Implementation of Corrosion Control Strategies," Project 157, funded 1994, published 2000, order number 90764). The research group evaluated the impact of plant-scale corrosion control measures on water quality characteristics such as red water, turbidity, and biological growth. They also developed mitigation strategies to decrease adverse effects caused by corrosion control processes.

Project results indicated that a utility can control the extent and severity of secondary effects in its distribution system by thoroughly evaluating its vulnerability to these effects and designing a corrosion control program appropriate for its system, particularly with respect to pH adjustment. The researchers urged utilities to avoid altering other treatment practices—changing the disinfectant or coagulant or adding other processes—at the time they implement corrosion control. Results also showed that ensuring the stability of water in the distribution system would help reduce the extent of secondary effects.

"Some utilities that switched to chloramines for DBP and biofilm control created a lead and copper problem, but not all utilities that use chloramines have corrosion problems," said LeChevallier. "We need to integrate all the information we have and look at corrosion control comprehensively to figure out the mechanisms that cause corrosion problems. Contributing factors can include lead, copper, iron, cement, pH, alkalinity, and corrosion inhibitors. If we oversimplify the problem, we get into trouble."

Distribution System Modeling

Computer simulations of distribution system hydraulics and water quality have become valuable tools for water utilities. "Hydraulic models can reliably tell us about the characteristics of distribution systems, including water flow and pressure," said LeChevallier. "Modeling is a tool we can use more effectively, and AwwaRF contributed to this through a variety of projects and workshops."

Tanks and reservoirs that store finished water are important components of distribution systems, and their design and operation also affect water quality. One of the most groundbreaking AwwaRF projects on distribution system modeling focused on water quality changes in storage tanks and reservoirs ("Water Quality Modeling of Distribution System Storage Facilities," Project 260, funded 1995, published 2000, order number 90774). Walter Grayman of Walter Grayman Consulting Engineers directed the project, and U.K. Water Industry Research was a research partner.

Storage facilities have traditionally been designed and operated to meet distribution system hydraulic requirements—providing emergency storage, equalizing pressure, and balancing water use throughout the day. But this project produced a tool to help utilities design, operate, and retrofit current and future storage facilities in order to maintain the highest water quality possible during distribution. The tool consists of a water quality model that overlies a hydraulic model; used in combination, the models can determine the effects of daily fill and draw cycles in storage tanks.

"Grayman developed a simple model that anyone can use to simulate mixing behavior in treated water storage facilities," said Charlotte Smith, president of Charlotte Smith & Associates, Inc., who also worked on the project. "Mixing behavior—whether water in the storage facility is stratified or mixed—affects the water's age, and age affects water quality. The model was called CompTank. The project also involved a computational fluid dynamics model and a monitoring component used to validate and verify the model."

This project also marked the first time computational fluid dynamics modeling was used to study drinking water storage facilities. This model, called HydroTank, can determine the concentration of disinfectant residual anywhere within a tank, allowing users to evaluate the impact of alternative designs and operating procedures on mixing behavior.

"The most important result of this study was that it raised awareness of the importance of mixing in tanks," said Smith. "It was also significant because of its design recommendations, some of which have been incorporated into state water works standards—for example, in California. One recommendation was that having a separate inlet and outlet on the tank allows better mixing."

Other project findings indicated that mixed-flow tanks are better than plug-flow tanks at reducing disinfectant losses, inflow and temperature conditions that lead to thermal stratification can be defined, and mixing times can be estimated as a function of tank geometry and inflow rates.

"The CompTank software is pretty handy; a number of utilities have used it to model mixing behavior in tanks," said Smith. "People have come up to me at conferences and said they found this project really useful. The *Journal AWWA* article reporting the study's results won the best paper award in its division."

The project report comes with a CD-ROM containing the CompTank software. A companion CD-ROM containing the HydroTank program is available only to AwwaRF subscribers as order number 90786.

Distribution System Monitoring and Sampling

Computer modeling is also playing a significant role in current approaches to distribution system monitoring and sampling. The two principal influences on this aspect of water utility operations are a provision of the Stage 2 D/DBP Rule and concerns about security.

Under the Stage 2 Rule, water utilities are required to conduct an IDSE—an initial distribution system evaluation—to identify sampling locations that have the highest DBP concentrations. Large utilities had to submit IDSE sampling plans in October 2006. "The utilities were allowed to submit hydraulic models or the results of grab samples, and most submitted models," said LeChevallier. "They're using models to identify distribution system areas with the longest hydraulic detention times—the oldest water—and that's where they're collecting DBP samples. These models are enabling us to be a lot smarter about monitoring," he said.

"Concerns about security have also changed our thinking about monitoring distribution systems," LeChevallier continued. "The traditional method—collecting a sample—gives us information about one point in space and time, rather than looking at the distribution network as a dynamic system that has spatial and temporal variations. The U.S. Environmental Protection Agency [USEPA] has done some modeling to assess where a contaminant intentionally put into a water system would travel and who would be affected. These dispersion models indicate we'd be better off doing frequent online monitoring in a few locations rather than collecting samples in a lot of locations less frequently," he said.

"Monitoring should be he same, whether you're dealing with contamination caused by a main break or by a terrorist," said LeChevallier. "Security-related research on monitoring indicates that grab samples are unlikely to detect these contaminants. Utilities need to invest in equipment that can report online information to the treatment plant instantaneously."

A reference book on online monitoring technology is available, thanks to a project jointly funded by AwwaRF and the Italian research organization CRS PROAQUA ("Online Monitoring for Drinking Water Utilities," Project 2545, funded 1998, published 2002, order number 90829). Erika Hargesheimer with the City of Calgary directed the project, collaborating with a group of international authors to produce the book.

Focusing on online monitoring applications in North America and Europe, the 13-chapter compendium describes state-of-the-art online technology, presents practical guidelines for using online monitoring instruments, and contains case studies and information on data handling. Individual chapters discuss the advantages and disadvantages of online monitoring; propose an approach to developing and standardizing performance measures; present test protocols for comparative evaluations; and describe basic operating principles, purchasing specifications, installation considerations, quality assurance and quality control measures, and maintenance and technical training requirements. The book's final chapter considers the future of online monitoring and identifies areas in which further research should be concentrated.

Several topics identified in the book are being examined in current AwwaRF projects. Among the goals of these studies are to identify the challenges and constraints associated with online monitoring of microbial and chemical contaminants, to develop data processing methods that can help water quality managers and operators spot abnormal patterns in online monitoring data, and to examine cost-effective ways to detect and mitigate toxicological attacks on distribution networks.

Pressure Transients and Intrusion

In addition to helping water utilities address distribution system issues related to disinfectant residuals, DBP formation, mixing behavior in storage facilities, and sampling and monitoring decisions, computer models have allowed providers to explore transient variations in distribution system water pressure.

Explaining the significance of transient pressure variations, LeChevallier recalled his experience as a Project Advisory Committee member for two well-known epidemiology studies conducted by Pierre Payment (with the University of Quebec at Laval) and funded by AwwaRF and several research partners. "These studies pointed to public health risks from properly treated water," LeChevallier said. "I felt that both studies implicated the distribution system as the source of illness and that the illnesses were probably viral (participants experienced mild gastroenteritis for a day or two and then recovered without going to a doctor or a hospital). Because viruses weren't getting through the treatment plant, and because they can't grow outside a host, how could they get into a distribution system?"

Pondering this question, LeChevallier concluded that only a momentary change in pressure would allow contaminants to enter the distribution system directly. He is now working on a fourth AwwaRF project to examine pressure transients and intrusion.

The first project indicated that all the circumstances that theoretically could cause pressure transients were, in fact, in place. The second project validated these concepts, verifying that low or negative pressure transients actually occur in real water distribution systems and that they can allow contaminants outside the pipe to intrude into a main through a leak or orifice ("Verification and Control of Pressure Transients and Intrusion in Distribution Systems," Project 2686, funded 2000, published 2004, order number 91001F). Both projects were co-sponsored by AwwaRF and USEPA and were directed by consultants at HDR/EES, Inc. Staff members at American Water also participated.

The second study consisted of several components, including an expert workshop, pilot-scale studies, and field testing in actual distribution systems.

"In the pilot-scale system, the researchers created and measured pressure transients and quantified intrusion volumes," said LeChevallier. "Then we monitored pressure in full-scale distribution systems. By collecting data from multiple systems, we accumulated millions of data points—the equivalent of more than ten years of data."

The study's findings indicated that direct contamination of a distribution system is possible as a result of occurrences of low or negative pressure caused by transient surges. The research group observed negative pressure events in three of the seven systems studied, and the pilot tests confirmed that intruded water is carried downstream from the leakage point. The group also produced guidelines to help utilities assess their susceptibility to low or negative pressures, control pressure surges, and minimize the impact of pressure transients should they occur.

"Transient pressures generally were related to power outages or pump shutdowns, so the conditions we observed matched our theories about how intrusion could happen," said LeChevallier.

A third project used hydraulic modeling to predict where pressure transients might occur. "The model helped us identify characteristics that can make a distribution system more susceptible to transient pressure events," said LeChevallier. "Factors that have to be taken into account include the velocity at which water is pumped into the system, changes in elevation, and the number of storage tanks involved."

The fourth project, still under way, deals with cross connection and backflow and is using online water quality monitors to assess the risks posed by intrusion. "Other intrusion studies have focused on contaminants entering the system through leaks, but another cause of low pressure is cross connections, in which water comes back into the system through service connections," LeChevallier said.

"The data show we have a potential problem, but we're not sure how much of a threat pressure transients are to public health," LeChevallier continued. Perhaps we need epidemiology studies, or we can just become more sophisticated in our approach to monitoring distribution system water quality. But we don't need to wait for epidemiology studies to know that maintaining pressure is an important aspect of maintaining water quality."

Applying this information to infrastructure, LeChevallier noted that "If we don't control pressure, we get more main breaks and more leaks, and we waste energy, which not only increases operations costs but also increases greenhouse gas emissions. All of these goals intersect. Maintaining water quality involves all of a utility's activities. We can't focus just on controlling DBPs, then on microbiological quality, and then on corrosion control. We have to take care of all these factors at the same time."

Water Quality Maintenance and Operations

A series of practical guidance manuals on maintaining distribution system water quality came out of several AwwaRF projects conducted between 1995 and 2005. Kirmeyer and his HDR/EES, Inc., colleague Melinda Friedman served as principal investigators for these projects.

The first of these studies, co-sponsored by UK Water Industry Research Limited, provided guidance on avoiding or correcting water quality problems in storage tanks and reservoirs ("Maintaining Water Quality in Finished Water Storage Facilities," Project 254, funded 1995, published 1999, order number 90763). Focusing on inspection and maintenance practices, the multidisciplinary research team examined issues such as microbiological contamination of tanks, biodegradation of tank coatings, screen failures, and avian contamination of uncovered reservoirs. Because loss of residual disinfectant is the most common problem in finished water storage facilities, the researchers suggested a target turnover rate of three to five days. They also recommended cleaning frequencies from six months for open reservoirs to five years for newer, well-maintained, covered storage facilities. The manual includes inspection forms and checklists.

Subsequent guidance manuals focused on best management practices for maintaining water quality throughout the distribution system. The second manual recommended operational, maintenance, and design practices to prevent or minimize water quality degradation and described treatment process changes to improve distribution system water quality ("Guidance Manual for Maintaining Distribution System Water Quality," Project 357, funded 1996, published 2000, order number 90798). The manual, which includes an interactive CD-ROM, summarized 14 case studies and five field studies and presented guidelines for distribution system flushing. The authors emphasized that the task of maintaining water quality in the distribution system crosses departmental boundaries, and they encouraged utilities to develop standard operating procedures to facilitate communication among all responsible parties. To this end, the manual proposes generic operating procedures to help utilities start this process.

The third manual in the series recommended distribution system auditing procedures and provided templates of distribution system optimization plans (DSOPs) for small, medium-size, and large water utilities ("Development of Distribution System Water Quality Optimization Plans," Project 2875, funded 2002, published 2005, order number 91069). The project was a tailored collaboration with the Cincinnati (Ohio) Water Works.

The manual notes that utilities can use DSOPs to optimize all distribution system functions that affect water quality or to target a few specific programs to improve water quality. It lists 11 examples of DSOP elements that utilities can apply to their own systems, including distribution system water quality goals, a monitoring plan, biofilm control strategies, programs for managing finished water storage facilities and dead-ends, and a unidirectional flushing program. The manual comes with a CD-ROM containing electronic versions of the example DSOP elements, a comprehensive audit form, and the template that allows a utility to develop its own DSOP.

Future Research Needs

USEPA has decided to use a negotiated rule-making process in revising the Total Coliform Rule (TCR), and these discussions are expected to highlight the most pressing research needs related to distribution system water quality. Some experts believe the new version of the rule may focus on distribution system operation and maintenance instead of the numeric evaluation of coliforms.

"The biggest challenge related to distribution system water quality is how we go about monitoring and sampling," said LeChevallier. "AwwaRF is currently funding some work on managing coliforms. As we collect larger volumes of samples, we observe that the rate of total coliform occurrence goes up, but *E. coli* concentrations don't go up. This research will be helpful to us in choosing the best indicator of distribution system contamination.

"The data lead us to conclude that *E. coli* is a better indicator of contamination," LeChevallier continued. "But we lack clear epidemiological and microbial risk data to link this information to public health outcomes." The problem, he explained is that "the Centers for Disease Control and Prevention collect public health data, and USEPA promulgates water quality regulations, but with these responsibilities divided, we don't have good information about whether theses regulations are enhancing public health."

Smith likewise pointed to the need for risk assessment and epidemiology studies. "We need research teams with expertise in both public health and drinking water operations to conduct these studies," she said.

Because of the importance of these issues, AwwaRF's board of directors in 2007 approved a strategic initiative for research related to distribution system water quality. A multiyear, multiple-project effort, the initiative is aimed at ensuring more complete, coordinated, and timely research in this area and at improving the dissemination of project results to AwwaRF subscribers and other stakeholders.