Drinking Water Quality Optimization: Focus on the Distribution System

David R. Wilkes

Water quality in a distribution system is affected by a complex interaction of many factors. The characteristics of water produced at the treatment plant can have a profound impact on changes that may occur in the distribution system.

Within the system, pipe materials, storage tank characteristics, and variable demand patterns all have an impact on the quality of water that reaches a customer's tap. At the same time, the distribution system is most vulnerable to tampering through vandalism or terrorism. It is no surprise, then, that the next regulatory focus will be on developing new rules directed at the distribution system.

This article provides an overview of the many elements that influence water quality in the distribution system and discusses optimization approaches that utilities should consider. The following areas are included:

- Biological stability and biofilms
- Corrosion and corrosion control
- Disinfection byproducts
- Aesthetic quality
- Optimization tools

Regulatory Framework

The distribution system has been primarily regulated for bacteriological quality (Total Coliform Rule), disinfection byproducts (THM Rule, Stage 1 D/DBP Rule, and Stage 2 D/DBP Rule), and corrosion byproducts (Lead and Copper Rule). Over the past several years, the U.S. Environmental Protection Agency (EPA) has indicated a desire to develop a distribution system rule that will address many issues affecting water quality that have not been regulated in the past.

The EPA, in association with distribution system experts, has begun to compile existing information regarding potential health risks that may be associated with distribution systems in "white papers" on the following nine distribution system issues:

- Intrusion
- Cross-connection control
- Aging infrastructure and corrosion
- Permeation and leaching
- Nitrification
- Biofilms/growth
- Covered storage
- Decay in water quality over time
- New or repaired water mains

In addition to these papers, the EPA, along with the American Water Works Association (AWWA), is preparing the following series of 10 Total Coliform Rule (TCR) issue papers on available information related to topics for potential TCR revision.

- Distribution System Indicators of Water Quality
- The Effectiveness of Disinfectant Residuals in the Distribution System
- Analysis of Compliance and Characterization of Violations of the Total Coliform Rule
- Evaluating HACCP Strategies for Distribution System Monitoring, Hazard Assessment, and Control
- Inorganic Contaminant Accumulation in Distribution Systems
- Distribution System Inventory and Condition Assessment
- Optimization of Distribution System Monitoring Strategies
- Effect of Treatment on Nutrient Availability
- Causes of Total Coliform Positive Samples and Contamination Events in Distribution Systems
- Total Coliform Sample Invalidation

All distribution system white papers and TCR issue papers will be used by the EPA to help develop any future distribution system regulations. As demonstrated by the breadth of these topics, the new rules have the potential to cover many issues on maintaining high-quality water in the distribution system.

The National Academy of Sciences has developed a study on water quality in the distribution system to help the EPA prioritize these issues. The first report (NAS, 2006) by the Committee on Public Water Supply Distribution Systems, *Assessing and Reducing Risks*, has been released, and the report indicates several high-priority issues the EPA should consider as it develops new distribution system regulations. The primary issues of greatest potential health risk are:

- Cross connections and backflow
- New or repaired water mains
- Finished water storage facilities

Two of these three issues are directly related to security risks and one is related to the vulnerability of systems when their physical integrity is breached to add or repair pipes. It is expected that the new distribution system rules will include elements that address these concerns. Based on this future regulatory framework, utilities should begin to assess their own systems and determine how best to optimize distribution system design, operations, and maintenance to meet these future rules.

David R. Wilkes, P.E., BCEE, is director of water treatment for the environmental engineering firm Jordan, Jones & Goulding Inc., working from the company's headquarters in Norcross, Georgia. This article was presented as a technical paper at the Florida Water Resources Conference in April 2007.

Water Quality Issues

"Unintended consequences" is a watchword for distribution system water quality. Many of the water quality issues that can develop in the pipe network and storage tanks depend on methods used (or not used) at the treatment plant.

Reducing organics to very low levels produces lower disinfection byproducts but may make copper pinhole corrosion worse. Adjusting pH higher to improve corrosion control may increase trihalomethane (THM) formation. Changing coagulants may improve organic carbon removal but may change the chemical makeup of the water and increase lead corrosion.

Adding new filtration techniques may improve microbiological quality but may allow passage of soluble inorganic compounds (e.g. manganese) into the distribution system, where oxidation with the residual disinfectant precipitates them and forms undesirable particles of aesthetic concern for consumers.

These examples indicate the need for a comprehensive analysis of water system components and the impacts of changes to them on distribution system water quality. This section includes the key water-quality issues that affect the distribution system and the latest thinking on managing those issues.

Biological Stability & Biofilms

Biologically stable water is less likely to support the growth of microbiological contaminants that may be introduced through the pipe network or that may have escaped

Continued on page 6

Continued from page 4
treatment. In Europe, biologically stable water is required in many countries because they do not maintain a disinfectant residual in the distribution system.

Stability is measured there using assimilable organic carbon (AOC). This measurement looks at the quantity of carbon in the water that is readily available as food for bacteria. Although the U.S. will never go to the European model of no residual disinfectant in the distribution system, incorporating methods of improving biological stability will also improve overall water quality.

Biofilms are a "coating" of a diverse community of organisms that form on pipe walls. The prevalence and vitality of biofilms are related to many factors, including (Camper, 2005):

- The type of carbon and its concentration
- The disinfectant type and concentration
- The type of pipe materials
- Corrosion control methods

Biofilms tend to form in large quantities in unlined iron pipe with a steady source of humic carbon, even in the presence of large concentrations of chlorine.

Optimizing water quality to increase biological stability and reduce biofilm formation is related to biological treatment of the water at the plant. Many plants that have introduced ozone as a disinfectant for *Cryptosporidium* control have added biological filters to remove ozonation byproducts such as aldehydes. These biological filters provide a biofilm on the filter media.

Typically, granular activated carbon (GAC) is used as the filter media because it provides more surface area and better sites for growth. The water quality produced by these filters has very low organics levels and tends to meet the low AOC levels found in European waters that are considered "stable." Utilities should consider biological filtration as one element of the treatment process that could potentially improve the overall biological quality of the water in the distribution system and reduce the chance for growth of opportunistic organisms that may find their way into the system.

The other optimization approach involves pipe material selection and replacement and optimum corrosion control. Since unlined iron pipe provides the best surface for biofilm growth, utilities should replace this type of pipe as a priority in their infrastructure management plans. Corrosion control using phosphate chemicals that produce a coating on pipe surfaces provides another barrier to biofilm growth and helps reduce the problem further.

Corrosion and Corrosion Control

Corrosion of the interior of iron pipe and the leaching of lead and copper have been the primary focus of corrosion control efforts in the distribution system. Recent events have indicated the complexity and difficulty in controlling corrosion.

In Washington, D.C., a switch from free chlorine to chloramines as a final disinfectant created a firestorm of controversy with lead levels increasing dramatically in the distribution system after the change. In Durham, North Carolina, lead levels increased after a change in coagulants was made to improve natural organic matter removal. The culprit appeared to be a change in the ratio of chlorides to sulfates that occurred after the switch.

In other places, copper pitting corrosion has become a huge issue with homeowners' plumbing, resulting in major collateral damage in terms of mold issues. These situations have indicated a need to look broader at the corrosion issue and develop more data on these complex interactions to ensure that the inorganic safety and aesthetic quality of the water in the pipes is maintained.

To ensure optimum corrosion control, each water must be studied for its unique characteristics. Recent history does indicate some key steps that utilities can take to ensure proper corrosion control.

For lead leaching issues, more research is underway on the interactions of chloramines and lead & copper. There have been no definitive cause-and-effect relationships developed that would be helpful to utilities considering chloramines.

Many other issues are now being evaluated with respect to chloramines, including the production of higher levels of N-nitrosodimethylamine (NDMA) in systems using chloramines, production of unregulated iodinated disinfection byproducts that may be more potent than any current byproducts, and the other well-understood issues of nitrification. For this reason, utilities should carefully consider all the implications before switching to chloramines for disinfection byproduct control.

Also, it is now understood that the ratio of chloride to sulfate in the distribution system has an impact on lead leaching from consumer plumbing. When this ratio is > 0.58, galvanic corrosion occurs and erodes particles of lead solder (ES&T, 2006). This new finding should cause utilities evaluating alternative coagulants to determine this ratio and consider alternatives that improve organics removal but keep this ratio below this threshold. Finally, research on copper pitting corrosion (Nguyen, 2006) has found the following key factors related to pitting development:

- Low concentrations of natural organic matter
- Aluminum residuals above 50 ppb as Al
- Free chlorine residuals above 2.5 mg/L
- Higher pH levels (above 8.2)
- Chloride levels less than 30 mg/L
- Frequent flow through the pipe (continuous flow being the worst case)

Since most utilities are controlling natural organic matter to low concentrations to reduce disinfection byproducts and (as noted previously) to control biofilm development, utilities should look to these other factors for methods to control copper pitting corrosion. Aluminum, pH, and free chlorine can definitely be controlled by optimizing their use at the treatment plant and avoiding these threshold values.

Another key element of corrosion control from an aesthetic perspective is for utilities to aggressively replace or rehabilitate old iron pipes. The production of "red water" and other color issues in the distribution system is directly attributable to interior pipe corrosion. Using phosphate-type inhibitors can be helpful in controlling release of these compounds, but the best approach is to remove the offending pipes from the system.

Optimizing phosphate inhibitors is another good corrosion control approach because it not only helps with lead and copper corrosion control, but also with biofilm reduction as noted previously. Also, research has indicated that orthophosphates in general are better for lead and copper control and polyphosphates are better for "red water" control.

Research has also indicated that polyphosphates alone may make lead leaching worse. For this reason, a blended phosphate with some ortho- and some poly- is probably best considered when multiple corrosion control objectives are desired.

Disinfection Byproducts

One of the most-researched water-quality issues in the distribution system is disinfection byproduct control. The new Stage 2 DBP rule changes the compliance approach, however, and many utilities will find themselves having to make significant changes to their treatment and distribution system practices to meet these new requirements. New, more potent disinfection byproducts also are being discovered and lead to the conclusion that reducing natural organic matter to very low levels before adding oxidants is an important optimization step for utilities to consider.

Dr. Philip Singer noted in a recent lecture (Singer, 2006) that optimizing disinfection byproduct control should focus on effective pretreatment for removing natural organic matter and reducing bromide in the source water, since brominated DBPs are the most potent in terms of health effects. As noted by Dr. Singer, many other benefits accrue when steps are taken by utilities to maximize natural organic matter removal. As noted previously, low organic levels also improve control of biofilms, so this optimization step has multiple benefits.

Other specific steps that utilities can take to improve disinfection byproduct levels after the treatment plant are outlined in the following sections.

Flushing programs. Many utilities have found that implementation of a systematic flushing program can improve water quality in the distribution system by reducing stale water in dead-end lines and by creating higher flows in areas of the system that have a long water age. Flushing is just another element of an overall distribution system water-quality program that may be useful in minimizing areas in the system with high DBP levels.

Storage tank improvements. Storage tanks may contribute to excessive DBP levels because of the nature of their hydraulic configuration and the lack of turnover in the tank contents during normal operations. An important element of any DBP reduction evaluation is sampling of tanks for DBP levels to determine if they are a potential problem. Modifications to tank inlet/outlet conditions, as well as operational changes to induce greater turnover, are possible modifications to reduce DBPs due to tanks.

In the past, distribution system storage tanks have served a hydraulic function to dampen peak-hour requirements and to provide fire protection storage. The tank designs were based on getting a quantity of water into the tank and out of the tank as easily as possible, so most tank designs have a common inlet/outlet pipe and result in dead spaces and water stagnation in the tank. Dead spaces and stagnation lead to higher disinfection byproducts, potential loss of chlorine residual, and deteriorated water quality.

By implementing systems that create completely mixed tank contents, detention times are reduced, dead spaces are eliminated, and water quality is greatly improved. As a proactive measure to ensure that tanks are not a major cause of water-quality problems, utilities should consider retrofitting tank mixing systems in all existing tanks and installing them in any new tank projects.

Reducing water age. A major contributor to continued DBP production in the distribution system is excessive contact time due to piping configurations and areas of reduced demand. Although many utilities may consider piping modifications an expensive method of DBP control, dead-end elimination through looping and other piping modifications may be the best solution compared to expensive alternative disinfectants or precursor removal options. These types of system modifications can be evaluated with a computer model using a number of "what if" situations relatively inexpensively to compare with other potential control strategies.

<u>Aesthetic Quality</u>

Color and taste/odor of water in distribution systems are important factors in maintaining consumers' confidence in the quality of their tap water. Major problems that contribute to consumer complaints are iron/manganese issues. These are typically related to high levels of soluble metals as well as precipitated compounds.

Many other issues are related to the "sloughing off" of corrosion products on pipe surfaces that lead to "red water" complaints. Other problems are odors that are produced from high doses of chlorine, misapplication of ammonia in the formation of chloramines, or "cat urine" odors associated with chlorine dioxide.

As noted previously, optimization of metals control is related to providing effective corrosion control chemicals and to effective removal of soluble iron and manganese in the treatment plant. If manganese, in particular, is allowed to pass through the plant, it inevitably gets precipitated in the distribution system because of the slow reaction kinetics at neutral pH with free chlorine oxidation.

Many utilities have these situations

Continued on page 8

Continued from page 7

occur on an intermittent basis and produce "pepper water" out in the distribution system. These sediments may lie dormant at the bottom of pipes until a hydraulic transient occurs that stirs them up and produces major complaints. An effective process for removing these soluble metals must be included in treatment facilities whenever they may occur so that no soluble metals are released to the distribution system.

For control of corrosion products, the key approach is aggressive pipe replacement as noted previously for other distribution water-quality problems. An effective use of phosphate inhibitors may help, but removing the source of the "red water" is preferable.

To control tastes and odors related to disinfection practices, treatment facilities have to monitor and control their use of disinfectants in an optimum manner. This optimization involves using only the amount of chlorine necessary to achieve disinfection at the plant and to maintain a residual in the distribution system.

For chloramines, strict adherence to best practices for chlorine-to-ammonia ratios and effective mixing at the point of addition will avoid any odors associated with di- and trichloramine formation. With chlorine dioxide, the best approach for controlling potential cat urine odors is the use of a ferrous compound to remove chlorite, since the reformation and volatilization of chlorine dioxide in the distribution system requires the presence of sufficient amounts of chlorite reacting with chlorine.

Optimization Tools

As utilities move forward with optimizing distribution system water quality, there are several approaches that ultimately will be combined to provide effective management. The two primary tools will be real-time water-quality monitoring and computer hydraulic modeling. This paper can not address the many important elements of these tools that will be required for optimization, but utilities should actively evaluate and analyze how to incorporate these tools in their water-quality management programs.

Real-time water-quality monitoring has one key application in terms of distribution system security. The most credible threat to drinking water systems from a water-quality standpoint is through intentional cross-connection contamination using any number of biological or chemical agents. For this reason, utilities should consider locating several continuous water-quality monitoring stations throughout the distribution system at strategic locations.

At a minimum, these stations should monitor chlorine residual and pH. There are many new technologies being developed for measuring other parameters that in the future may be useful; however, current systems being implemented can monitor these two parameters as well as other basic constituents, such as turbidity and conductivity.

Many (but not all) of the biological agents that might be used by terrorists are susceptible to chlorination. A well-planned attack on a water system with one of these agents would most likely be preceded by adding a dechlorinating agent to the distribution system to ensure maximum infection by those affected. With continuous chlorine monitoring and alarming of this data, early warning of a possible attack would be provided.

Also, many toxic chemicals would have to be delivered in concentrated form to induce the kind of injury desired by a terrorist. These concentrated forms typically would be either acidic or basic and would affect the pH of the distributed water significantly, once they were introduced in continuously-fed, large quantities.

The location of these monitoring stations should take into account the potential ability of a terrorist organization to lease space and set up the equipment necessary to store and deliver large quantities of agent (i.e. major commercial, warehouse or industrial areas). Locating the monitoring facilities downstream of major tanks or in important concentrations of population (university area, schools, etc.) would be prudent.

Specific locations will also have to take into account the vulnerability of the units to being destroyed by a terrorist operation. Connecting these stations to the main water system control facilities through SCADA will be required.

In general with the methods proposed, water quality protection can not be completely assured against agents that are colorless, inorganic, odorless, and tasteless. The additional monitoring suggested here, however, provides valuable operational information while reassuring the public that the water in their pipes is being continuously monitored for protection against a terrorist attack.

Computer hydraulic modeling is a tool that ultimately will be used for managing water quality in distribution systems. Modeling currently is used by many utilities for compliance with the Initial Distribution System Evaluation requirements of the Stage 2 DBP rule. By using a well-calibrated model, the age of water in the system can be determined and effective options for reducing age can be modeled. Since water age has many negative water-quality effects, managing this parameter will significantly improve overall distribution system water quality.

In the future, major pipeline and storage tank projects will be analyzed not only for their hydraulic feasibility using the computer model, but also for their impact on water age, and thus, water quality. The computer model allows analysis and comparison of alternatives that will provide the optimum solution for hydraulic performance while also providing optimum water quality.

Utilities will eventually integrate GIS systems with the models to track complaint data and retrieve real-time water-quality information from the monitoring stations. Linking these two tools ultimately will provide much more effective operation and control of distribution systems to ensure the highest-quality water possible for customers.

Summary

There are many approaches utilities can take to optimize water quality in the distribution system. The following provide the best chance for making major improvements and maintaining high-quality water in the system:

- Replace or rehabilitate unlined iron pipes on aggressive schedules to remove them from the system.
- Remove as much natural organic matter as possible prior to addition of an oxidant or release to the distribution system.
- Produce biologically stable water.
- Practice effective corrosion control for all types of corrosion.
- Remove insoluble metals (particularly manganese) in the treatment plant.
- Use water-quality monitoring and computer hydraulic modeling as optimization tools.

Given the increased focus of regulators and consumers on the quality of water in the pipes, utilities must begin adopting a management approach that focuses on optimizing and producing the best possible water in the distribution system.

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