Tools for Evaluating and Managing Distribution System Water Quality

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Historically, drinking water regulations have focused on the removal (or inactivation) of naturally occurring constituents, contaminants, and microorganisms at the treatment plant. Accordingly, utilities have, for the most part, attempted to minimize water quality degradation in the distribution system by modifying treatment practices at the plant.

As new regulations increasingly focus on maintaining distribution system water quality, utilities are also beginning to shift their focus from the treatment plant to the distribution system. Utilities are finding that many of the typical distribution system water quality problems they experience are best remedied using more effective distribution system management practices, rather than modifications at the treatment plant.

Distribution system optimization may be sufficient and more cost-effective than many of the in-plant solutions typically used. For example, if one small area of the system has known water quality issues, it can be much more economical to focus on that area of the system, rather than implement a system-wide impact. Focusing on a specific area of the system also helps to minimize the potential for unintended consequences associated with system-wide solutions, such as corrosion control impacts, nitrification, and taste and odor.

In addition, in-plant solutions may not always be effective. Many distribution system water quality issues are the result of physical or operational factors that are not impacted by treatment solutions. In such cases, it may not only be more practical or economical to focus on distribution system solutions rather than in-plant solutions, but it might be the only option available.

Drivers for Managing Distribution Water Quality

The goal of every public water system is to provide high quality drinking water to its customers. This is accomplished by various combinations of source water management, treatment, and distribution system management. Of these three strategies, distribution system management may be the most critical and difficult. If one assumes water quality leaving a treatment plant is at its highest, then the goal of distribution system management is to minimize water quality degradation from the treatment plant to the consumer tap.

Regulatory Drivers

The first attempt to regulate distribution system water quality was the Total Trihalomethane Rule in 1979. Since that time, there have been a number of drinking water regulations focused on maintaining treated water quality and minimizing water quality degradation from the distribution system entry point to the tap. These regulations focus on disinfection byproducts (the Stage 1 and 2 Disinfectant and Disinfection Byproduct Rules), disinfection and microbial water quality (Surface Water Treatment Rule and Total Coliform Rule), and corrosion byproducts (Lead and Copper Rule).

In the early 2000s, the U.S. Environmental Protection Agency (USEPA) issued a series of white papers regarding distribution system factors that impact distributed water quality and have the potential to impact public health:

- Water age
- Poorly managed storage facilities
- Biofilms and microbial growth
- Nitrification
- Cross-connections and backflow
- Main replacement and maintenance
- Aging infrastructure
- Permeation and leaching
- Intrusion

The nine issue papers were discussed during the Revised Total Coliform Rule/Distribution System Rule (rTCR/DSR) rulemaking process. Though no regulatory determination was made on the specific nine issues, what resulted from the rTCR/DSR Federal Advisory Committee (FACA) were seven technical topic areas deemed most relevant to protecting public health and maintaining the integrity of drinking water distribution systems. These topic areas were further divided into Tier One and Tier Two topics. Tier One topics are known to have documented public health outcomes. Some information is available to characterize the extent or occurrence of Tier One issues, however more national-level characterization of the occurrence and relationship to health outcomes are needed. Finally, there are some best practices available to control Tier One issues. For Tier Two issues, there is some evidence that they do occur and adverse public health impacts are suspected, but little information is available to document or characterize the occurrence and related health impacts of Tier Two issues. The seven topic areas are summarized:

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TIER 1

1. Cross-connections and backflow of contaminated water.
2. Contamination due to storage facility design, operation, or maintenance.
3. Contamination due to main installation, repair, or rehabilitation practices.
4. Contaminant intrusion due to pressure conditions and physical gaps in distribution system infrastructure.

TIER 2

1. Significance and control of biofilm and microbial growth.
2. Nitrification issues that lead to public health effects.
3. Accumulation and release of contaminants from distribution system scales and sediments.

The interesting thread that ties the seven topic areas together is the shift from conventional regulation based on a maximum containment level (MCL) to potential regulation of distribution system design, operation, and maintenance. Future distribution system regulations are likely to focus on best practices, rather than contaminant concentrations. Although regulation of any one of these specific topic areas is several years in the future, understanding these priority areas and how one's own utility is positioned to deal with these issues is a much-needed next step in protecting public health and positioning for future regulatory compliance.

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Additional Drivers

The American Water Works Association (AWWA) estimates that nearly $1 trillion in buried infrastructure investment is needed in the United States in the next 25 years. There is significant financial incentive to manage distribution system water quality, design, and operation to extend asset life and reduce infrastructure replacement needs. Unaccounted-for water (water loss) represents a significant lost source of income to water utilities. Excessive water loss is also counter to being good stewards of the environment and all precious natural resources. Minimizing corrosion and maintaining distribution system integrity not only can help to reduce water loss, but also reduces the potential for contamination of the system and the associated risk to public health.

In addition to the financial and public health benefits, there are also other reasons to maintain water quality. Color, taste, and odor, though they may not have any health impacts, certainly impact customer perception of water utility. Taking steps to improve customer perception can significantly benefit the consumer/utility relationship, resulting in increased public support of the utility. In these difficult economic times, that can help with needed rate increases.

Factors Influencing Distribution Water Quality

Distribution system water quality can be impacted by a number of elements, including water quality and chemical factors, design or physical factors, and operational factors. Understanding how each of these impacts water quality is essential to developing a strategy to maintain distribution system water quality.

Table 1 summarizes some of the factors that can impact distribution system water quality and strategies to address them. It is not intended to be a complete list of the potential impacts, nor is it intended to identify all of the factors and control strategies. It is provided for illustrative purposes to show that managing distribution system water quality is a complex and challenging process, and that many of the factors that influence water quality may be beyond the control of the utility.

Note in Table 1 that although there are a number of "in-plant" solutions to address distribution system water quality issues (e.g., enhanced treatment), there are a substantial number of distribution system strategies that can also be implemented. In-plant solutions can be effective for the control of widespread distribution system water quality issues associated primarily with chemical or water quality factors; however, they may be of limited or no effectiveness in dealing with physical or operational factors. Further, when distribution system water quality issues are localized, implementation of a distribution system control strategy can be equally effective and less costly than treatment plant solutions.

Table 1. Factors Influencing Distribution Water Quality

Factor Type	Examples	Control Strategies
Chemical/Water Quality	- low pH - high chloride:sulfate ratio - excess free ammonia - improper inhibitors - low disinfectant residual - low/high alkalinity - high organics	- treatment modifications - proper chemical selection - better chemical dose control - disinfection optimization - booster disinfection
Physical	- pipe materials - dissimilar metals (galvanic) - dead ends - oversized mains - excess storage - failing infrastructure	- service line replacement - pipe replacement - cathodic protection - "right sizing" mains - decommissioning storage - pipeline replacement
Operational	- high velocities (erosion) - low velocities - high water age - poor storage facility operation - pressure transients	- operational modifications - water age management - storage facility management - installation of VFDs

Table 2. Example Nitrification Distribution System Monitoring Parameters
(Adapted from Smith, 2006)

Parameter/Usefulness		
Level 1 (Baseline)	**Level 2 (Supplemental)**	**Level 3 (Diagnostic)**
Total Chlorine	Nitrate-N**	Dissolved Oxygen
Nitrite-N	Total ammonia-N	TOC
Free ammonia-N	HPC-R2A	Hardness
Temperature		Alkalinity
pH		AOB***
Free Chlorine*		

* Very useful during breakpoint chlorination (not for routine monitoring)
** Very useful if background nitrate-N level is consistent
*** Limited usefulness until rapid inexpensive enumeration methods are available

Evaluating Distribution System Water Quality

There are a number of tools available to evaluate distribution systems, including water quality data, hydraulic models, and geographic information systems (GIS), and they can be used in various combinations. The following discusses the applicability and limitations of several of these methods.

Water Quality Data

Water quality data can be very helpful in diagnosing distribution system water quality issues and identifying solutions. To be useful, utilities must have the right data available. Every utility is required to collect some distribution system water quality data by regulation, such as disinfectant residuals, disinfection byproducts (DBPs), and corrosion water quality parameters. In most cases regulatory monitoring requirements alone are insufficient as a tool for evaluating what is actually happening in the distribution system. For example, under the Total Coliform Rule every utility is required to monitor for coliform and disinfectant residual on a monthly basis at a number of locations in the distribution system. For a system on chloramines, that data alone is insufficient for evaluating much else. Conducting supplemental water quality monitoring in addition to regulatory (required) monitoring is critical to evaluating the distribution system.

The first step in developing a monitoring program is to determine how the data might be used. Is corrosion the concern, or is it DBPs, or perhaps nitrification? After determining the goals of the monitoring program, it is then necessary to identify appropriate monitoring parameters. Table 2 presents an example nitrification monitoring program. Level 1 parameters are monitored on a routine basis. Level 2 parameters are monitored during periods when nitrification is known to occur, or in locations where nitrification is suspected to be occurring based on Level 1 data. Level 3 parameters are used only in the event of a nitrification event and to help narrow the cause of the event, if necessary. Level 3 parameters are rarely monitored.

Poorly mixed and poorly operated storage tanks can have significant impacts on distribution system water quality. Table 3 presents temperature, free chlorine, total trihalomethanes (TTHMs), and haloacetic acids (HAA5) concentrations in the top and bottom of three tanks. The data demonstrate how water quality is impacted by storage facility operations.

Tank 1 Significant variation in free chlorine concentrations at the top and bottom of the tank are indicative of poor tank mixing. As a result, DBP levels in the top of the tank are approximately 33 percent higher than in the bottom of the tank. This can result in slugs of poorer water quality entering the system and jeopardize compliance.

Tank 2 The DBP levels in both the top and bottom of this tank are high and pose potential problems. Thermal stratification and significant variations in free chlorine are indicative of poor mixing. In this case, because there is very little chlorine left in the top of the tank, DBP formation has nearly stopped.

Tank 3 Again, significant variations in free chlorine concentrations at the top and bottom of the tank are indicative of poor tank mixing. Because there is no chlorine remaining in the top of the tank, DBP formation has stopped, and biodegradation of HAA5 has begun as evidenced by the lower concentration in the top of the tank.

Table 3. Evaluation of Storage Tanks Using Water Quality Data

Tank Type (Volume, Mgal)	Temperature (° F)		Free Chlorine Residual (mg/L)		TTHM (µg/L)		HAA5 (µg/L)	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Elevated (1.0)	79	78	1.0	1.7	100	76	82	61
Elevated (0.5)	81	77	0.1	0.8	120	110	86	75
Standpipe (4.0)	81	80	0.0	1.0	98	99	31	61

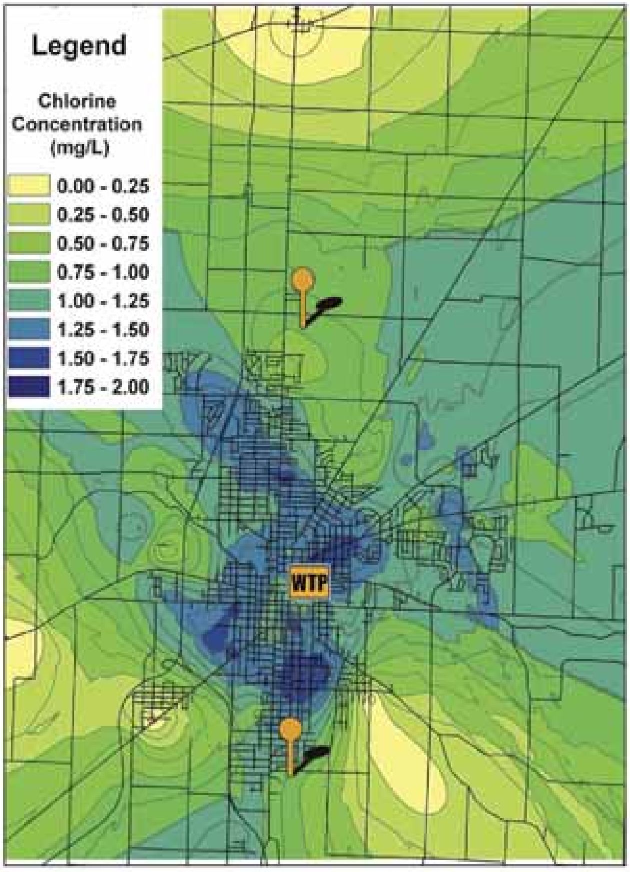

Figure 1. GIS Chlorine Residual Contour Map

Modeling and Geographic Information Systems

Distribution system hydraulic models can be an extremely valuable tool for evaluating distribution systems. They are primarily used to estimate water age, but can also be used to estimate water quality, such as chlorine residual. Where they are particularly useful is in the evaluation of changes in operation or physical configuration of the distribution system and the impacts to water age. A reasonably complete, well-calibrated model is almost a necessity today if one intends to seriously consider managing of distribution system water quality.

Computational fluid dynamic (CFD) modeling is an effective tool for evaluating storage tank operations. The CFD modeling can also be used to effectively evaluate the impact of design changes on mixing characteristics. The CFD software packages can be expensive and are not necessary to evaluate storage tank mixing characteristics. The Water Research Foundation has released a special-purpose CFD package, HydroTank, solely for evaluating storage tank mixing. The package is available as a part of the report, *Water Quality Modeling of Distribution System Storage Facilities* (Grayman, et al., 2000). This report also includes a detailed discussion of CFD modeling and its applicability to evaluating storage tank mixing characteristics.

Another powerful tool for the evaluation of distribution systems is GIS. It can be used to spatially locate water quality data and complaints, and when combined with a hydraulic model, can give a very accurate representation of what is occurring in the distribution system. It also allows for more useful visualization of distribution system water quality. For example, Figure 1 shows a chlorine residual contour map-generated GIS using monthly chlorine residual monitoring data. The lighter areas in the figure represent low disinfectant residual and are focus areas for distribution system improvements to increase water quality.

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Managing Distribution System Water Quality

To accomplish distribution system water quality, it is necessary to determine which factors can be controlled and develop strategies to address them

Storage Tank Operations

Increasing volume turnover and improved tank mixing are the two most effective strategies for minimizing water age in storage tanks and improving distribution water quality. Volume turnover in storage tanks is generally expressed in one of two ways: the percent of volume that is exchanged in one day, or the average time that the entire volume of water is discharged from the storage facility. A minimum turnover of three to five days (20 to 33 percent turnover per day) is recommended (Kirmeyer, et al., 1999). Figure 2 shows an example of tank levels in a well-operated tank over a 24-hour period. Note that when the tank is draining, it drains to a set low tank level before filling, and then fills until it hits a high tank level. This is optimum from a turnover and mixing perspective.

Inlet momentum (velocity × flow rate) is a key factor for mixing of water in storage tanks; the higher the inlet momentum, the better the mixing characteristic in the storage tanks. Increasing the flow rate is one way to increase inlet momentum, but it may not be practical due to limitations of system hydraulics. For example, a pump may not be available at the tank location and the distribution system pressure may not be high enough to get desirable increases in flow rates. In some cases, even if a pump were available, it may not be possible to increase the pumping rate into the tanks. In such cases, it may be more feasible to increase the inlet momentum by increasing the velocity with a reduced inlet diameter.

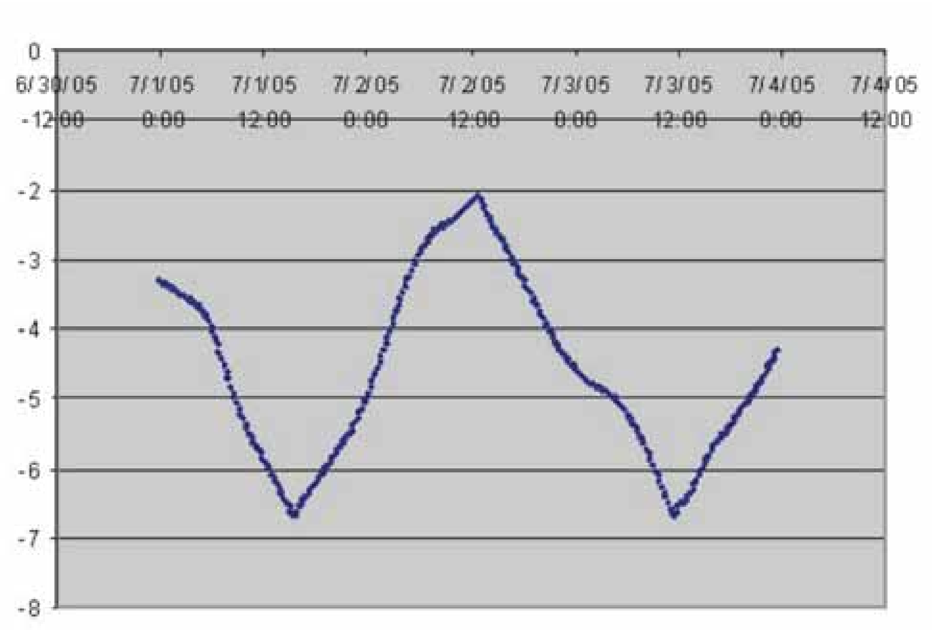

Figure 2. Example of a Well-Operated Tank

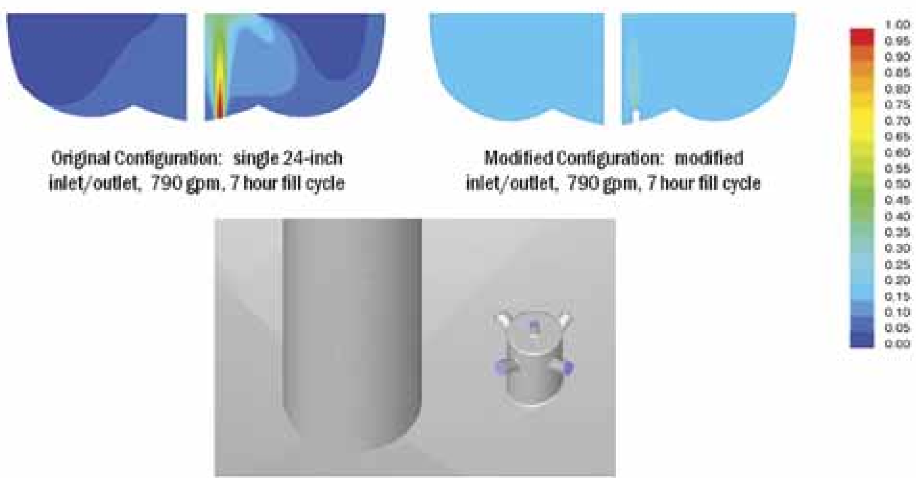

Figure 3. Impact of Inlet Configuration on Tank Mixing.

To encourage good mixing, the inlet should be directed away from any obstacles, such as a tank wall, the bottom of the tank, or deflectors (Grayman, et al., 2000). The location and orientation of the inlet pipe relative to the tank walls can have a significant impact on mixing characteristics. For example, when the height of a tank is much larger than the diameter or width, the location of the inlet pipe at the bottom of the tank in the horizontal direction is likely to cause the water jet to hit the vertical wall of the tank, resulting in loss of inlet momentum and incomplete water mixing.

Figure 3 shows the impact of inlet orientation on tank mixing and shows improvements implemented to advance tank mixing and water quality. The tank depicted is a 2-mil-gal elevated storage tank. The tank had a single 24-in. inlet/outlet located to one side of an access manway. The inlet momentum was insufficient to completely mix the upper levels of the tank, and the manway was a barrier to mixing in half of the tank. A modified inlet/outlet, consisting of four 8-in. nozzles directed to the upper quadrants of the tank and a 6-in. nozzle directed vertically, was able to achieve complete tank mixing without modifications to any of the other operating conditions.

Baffles are used to encourage plug flow and to eliminate short-circuiting and dead zones in contact tanks. Plug flow in distribution system storage facilities results in increases in water age, higher DBP levels, and loss of disinfectant residual. Consequently, baffles should be avoided in distribution system storage facilities to reduce water age, increase disinfectant residuals, lower DBP concentrations, minimize the potential for nitrification, and generally improve water quality.

Water Age Management

As discussed, improving tank turnover and mixing can significantly reduce water age in the distribution system, but the design and operation of the distribution system can also significantly impact water age. Dead ends, areas with low flow, oversized distribution mains, and excessive storage increase water age and can result in loss of residual, increases in DBP levels, and nitrification. Looping to eliminate dead ends and increase flow in low-flow areas can reduce water age and improve water quality; however, care must be taken to ensure adequate demand exists to induce flow in the area. Otherwise, looping may just create a larger dead-end zone.

Most water systems are designed based on fire flow rather than water quality requirements. This results in a lot of oversized water mains with low flow and high water age under normal operating conditions. In other cases, reduction in demand (e.g., loss of a large industrial user) or designs based on future demands that have yet to come can also result in excessive water age. The problem often compounds itself as water moves through the system, resulting in very high water age and DBP levels at the ends of the system. The installation of smaller mains or parallel mains (which also improves system redundancy) is one method to help control water age. Inducing higher system demands by adding new industrial users, flushing, or blowoffs can also be an effective strategy for controlling water age and reducing DBP levels. For example, the City of St. Petersburg recently converted several public parks from reclaimed water to potable water for irrigation to address water age-related water quality issues in the ends of its distribution system.

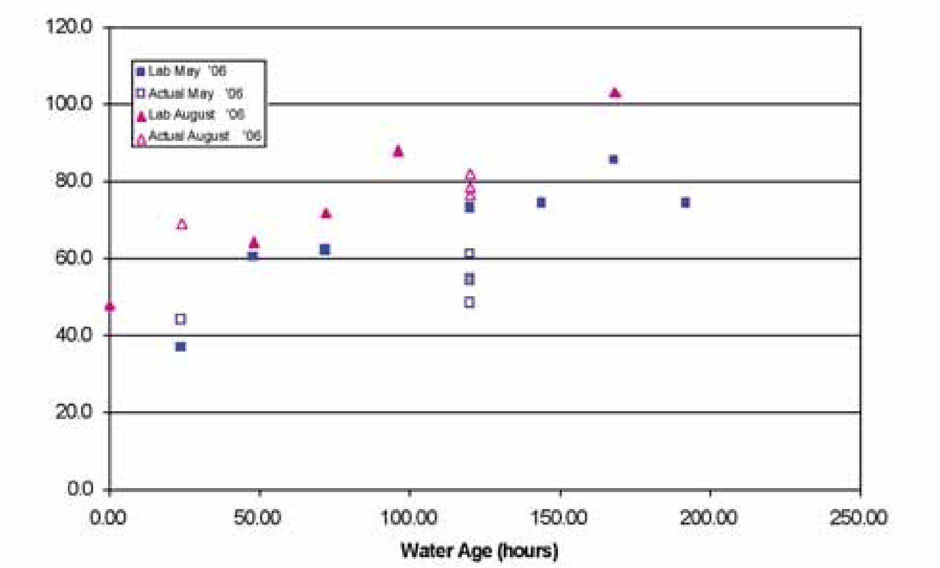

Figure 4. Effect of Flushing on Consecutive System TTHM Concentrations

Flushing

Flushing can be a very effective short-term response to distribution system water quality issues. It can remove distribution system sediment and biofilms, reduce disinfectant demand, and reduce water age. Most utilities conduct flushing on a regular basis, usually related to fire hydrant maintenance rather than water quality maintenance. Emergency flushing (or spot flushing) is often performed in response to customer complaints for color, taste, or odor problems, and in response to other water quality problems, such as insufficient disinfectant residual, evidence of nitrification, or positive coliform results.

There are basically two types of flushing: conventional and unidirectional. Conventional flushing is conducted by opening hydrants (it does not include directing the flow with valves) and is often considered routine distribution system maintenance. When conducted on a regular basis, conventional flushing can be used to remove older water from the system and allow fresher water to enter the affected area. With this method, it is difficult to control the quality of water entering the main being flushed and it is possible that the quality of this water may not be superior to that leaving the system. In addition, conventional flushing may be less than optimal in controlling other factors that can contribute to water quality degradation, since, in most pipes, a velocity of 5 to 6 ft per second (fps) is required to remove sand, sediments, corrosion byproducts, and other debris.

Unidirectional flushing is conducted in a systematic manner directing the flow to enhance the flushing of the desired main; essentially, clean a main then use that main to clean the next in a carefully planned manner. A properly designed and implemented unidirectional flushing program can achieve water velocities greater than 5 fps and can scour the pipe. In addition to increasing water flow in the selected main, unidirectional flushing can reduce the impact of other factors contributing to water quality degradation, including biofilms, the accumulation of sediments, and the buildup of corrosion byproducts.

The problem with traditional flushing programs, whether conventional or unidirectional, is that the water quality benefits are likely to be short-lived. Automatic flushing can provide the benefits of flushing on a regular basis and result in long-term water quality improvements. Figure 4 shows the effect of automatic flushing on distribution system DBP levels in one Midwest utility. In this case, the local water utility acquired a small consecutive system that was connected to the main system by an approximately 4-mi-long, 16-in. transmission main. The consecutive system had approximately 400 residents and an average day demand of about 40,000 gal. Water age increased in the transmission main by approximately five days, resulting in low chlorine residuals and high DBP levels in the distribution system. The utility chose to implement automatic flushing at two locations in the consecutive system. As a result of the flushing, water age decreased in the consecutive system from seven to ten days to four to seven days, chlorine residual increased, and DBP concentrations were reduced by 30 to 40 percent.

Conclusions and Recommendations

There are a number of tools available to evaluate distribution systems and develop strategies to maintain distributed water quality. Distribution system optimization may be sufficient and more cost-effective than many of the in-plant solutions typically used. In addition, in-plant solutions may not always be effective. Many distribution system water quality issues are the result of physical or operational factors that are not impacted by treatment solutions. In such a case, it may not only be more practical or economical to focus on distribution system solutions rather than in-plant solutions, but it might be the only option available.

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