

Ohio AWWA  
Joint Distribution/Technology Committee  
Distribution Systems Subcommittee

White Paper on Distribution System Optimization for Water Quality

April 14, 2014

**Purpose**

The purpose of this white paper is to assist Ohio drinking water utilities in identifying and implementing strategies to optimize distribution system performance with regard to water quality. Most water distribution systems are designed based on quantity requirements (i.e., consumer demand, fire flow, and pressure requirements), and little regard is given to water quality. Recent research and regulations have, however, identified the potential impacts of the distribution system on water quality, and forced drinking water utilities to evaluate the impacts of distribution operation on their own water quality.

This white paper is not intended to provide significant detail with regard to distribution system optimization strategies. Rather, it discusses distribution system factors that contribute to water quality degradation and provides an overview of evaluation and optimization methods and strategies related to those factors. Where additional guidance or direction is necessitated, this paper identifies and recommends additional references and sources of information.

**List of Acronyms**

**Background and Objectives**

Distribution system optimization for water quality can help to reduce water age and disinfection byproduct (DBP) concentrations, improve disinfectant residual maintenance, minimize corrosion, and eliminate taste, odor, color and other aesthetic water quality problems. This document is available to utilities for the purposes of identifying distribution system factors that impact water quality. It discusses methods for evaluating the impacts of these factors and recommends strategies to improve distributed water quality. It also includes additional references and sources of information in which greater detail can be found regarding the implementation of distribution system optimization strategies.

It is not the intent of this white paper to provide great detail regarding distribution system optimization strategies to enhance distributed water quality. Rather, it is the goal of this paper to educate the Ohio drinking water community with regard to practices being undertaken by other drinking water utilities around the country to improve water quality by optimizing the distribution system. Distribution system optimization is recognized as a valuable tool as it relates to improving water quality and meeting current and future drinking water regulations.

The Stage 2 Disinfectants and Disinfection Byproducts Rule (DBPR) identifies “hydraulic flow and storage management” as best available technology (BAT) for consecutive drinking water systems attempting to comply with the total trihalomethane (TTHM) and haloacetic acid (HAA5) requirements of the rule (71 FR 388-493).

The purpose of this white paper is to help public water systems (PWS) identify distribution optimization strategies for the purposes of enhancing distributed water quality. Where additional water quality monitoring is discussed or recommended, PWS are encouraged to discuss their distribution system water quality monitoring program with the Ohio Environmental Protection Agency (Ohio EPA) to assure these samples will not be used for compliance purposes and will not be required to be reported in annual Consumer Confidence Reports (CCR).

### **Other Applicable Guidance**

AwwaRF, *Assessing and Controlling Bacterial Regrowth in Distribution Systems*  
AwwaRF, *Development of Distribution Water Quality Optimization Plans*  
AwwaRF, *Distribution Water Quality Changes Following Corrosion Control Strategies*  
AwwaRF, *Guidance Manual for Maintaining Distribution Water Quality*  
AwwaRF, *Guidance Manual for Monitoring Distribution System Water Quality*  
AwwaRF, *Online Monitoring for Drinking Water Utilities*  
AwwaRF, *Guidance for Management of Distribution Systems Operation and Maintenance*  
AwwaRF, *Implementation and Optimization of Distribution Flushing Programs*  
AwwaRF, *Maintaining Water Quality in Finished Water Storage Facilities*  
AwwaRF, *Assessment of Existing and Developing Water Main Rehabilitation Practices*  
AwwaRF, *Water Quality Modeling of Distribution System Storage Facilities*  
AwwaRF and DVGW, *Internal Corrosion of Water Distribution Systems*  
AWWA G200, *Distribution Systems Operation and Management*  
AWWA Emergency Response Toolbox  
AWWA, Manual of Water Supply Practices M56, *Fundamentals and Control of Nitrification in Chloraminated Drinking Water Distribution Systems*  
AWWA, Manual of Water Supply Practices M 58, *Assessment and Control of Corrosion and Metals Release in Drinking Water Distribution Systems* (in progress)  
USEPA, *Operational Evaluation Guidance Manual* (in progress)

“Special purpose” samples collected for the purposes of distribution system optimization are not required to be reported to the Ohio EPA. All samples marked “For Compliance” are required to be reported to the Ohio EPA.

### **Acknowledgements**

This document reflects a collaborative effort between members of Technology Committee and Distribution Committee of the Ohio Section of the American Water Works Association and Ohio EPA. Ohio EPA and the Ohio Section wish to acknowledge the following Subcommittee Members for their contributions to this effort.

Brian Bisson, *Aqua Ohio*  
Jeff Davidson, *Ohio EPA*  
Chris Hill, *Malcolm Pirnie*  
Yeongho Lee, *Greater Cincinnati Water Works*  
Matt Steele, *Columbus Division of Water*  
Jeff Swertfeger, *Greater Cincinnati Water Works*

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## 1.0 INTRODUCTION

Distribution system physical and operational characteristics have the potential to significantly impact water quality, hydraulic capacity, and operations costs. In addition, managing distribution system water quality can help to maximize the life of system components (e.g., by minimizing corrosion or scale on system valves). Optimization of distribution systems physical and operational conditions has the potential to achieve the following:

- Improve water quality
  - Reduce disinfection byproducts (DBPs)
  - Minimize microbial events, including Total Coliform Rule (TCR) violations
  - Improve disinfectant residuals
  - Reduce corrosion and minimize scale deposition
  - Minimize taste and odor complaints
  - Minimize color complaints
  - Reduce overall customer complaints
- Improve hydraulic efficiency
- Reduce pressure gradients and hydraulic surges (water hammer)

This white paper focuses on optimization of distribution systems for the purposes of improving water quality; however, it does make reference to hydraulic capacity and operations costs, where appropriate and where optimization may impact these other areas of importance.

There are a number of tools available to utilities for the purposes of evaluating distribution system characteristics and identifying improvements to enhance water quality. These tools include:

- Water quality monitoring
- Desktop and computational fluid dynamic (CFD) modeling of storage facilities
- Flushing
- Hydraulic and water quality modeling.

This white paper is intended to provide the reader with insight into the cause of water quality problems resulting from distribution system operational issues, as well as identify appropriate tools to identify the cause and appropriate response measure. It is not a prescriptive document. That is, it does not present a one-size-fits-all approach to distribution system optimization. Rather, it provides useful information, including additional resources, to utility managers and system operators to make informed decisions regarding distribution system optimization and to assist in developing a distribution system optimization plan.

## 2.0 WATER QUALITY MONITORING

### 2.1 Importance of Water Quality Monitoring

Water quality monitoring is fundamental to the proper operation of a public water supply system. The primary goal of any water monitoring program is to ensure the safety and quality of the water delivered to the public. Typically water quality monitoring programs have focused on

regulatory compliance. But, water quality monitoring can achieve many more goals than just regulatory compliance. Monitoring programs can be used for operational management (water age, nitrification, mixing issues, booster chlorination), maintenance scheduling (flushing, tank cleaning, main repair pipeline rehabilitation/replacement, return to service), support capital improvement projects, system security, and to detect and improve customer complaints (rusty, T&O, secondary MCLs).

## **2.2 Developing a Baseline Water Quality Monitoring Program**

A baseline water monitoring program can be defined as sampling at regular intervals over a period of time at the same group of locations. This regular data collection gives the utility a starting point to track water quality changes and give them information to meet their monitoring and operational goals. There are three steps involved in developing a monitoring program: planning, design, and implementation.

### **2.2.1 Planning**

Planning is the key to having a successful monitoring program. This phase is where the utility decides on their monitoring goals, establishes the resources (budget, staffing, etc.), and determines who the end user will be (management, operations, etc.). To begin a baseline monitoring program the utility must first take inventory of its regulatory monitoring requirements. Generally, this will be the starting point for a monitoring program. Once the regulatory sites are inventoried, then the utility can begin to explore other options for expanding their program.

Other considerations in establishing a monitoring program are: system size and water quality variability throughout the system.

### **2.2.2 Design**

The design phase is where the utility decides on: parameters to be tested, sampling frequency, sample preservation (ice, preservative), holding times of parameters to be tested, types of equipment, laboratories for testing, and finally sample site selection to meet their established monitoring goals.

Site selection is very important in having a valuable monitoring program. Begin with things that are already known, like: historical monitoring locations, operator experience, and customer complaints. Site selection criteria can include: location in the system and age of the water (near the entry point, average residence time, or near the end of the system), ease of access, mixing zones (if more than one water plant), storage and booster pumping facilities, water main size and material, booster chlorination locations, and critical users.

Another consideration during the design phase is to determine how the data will be managed (gathered, stored, manipulated, reported, etc.).

### **2.2.3 Implementation**

The implementation phase is where the utility begins the collection and management of the data. They also begin to understand their normal water quality variations in the system. In this phase utilities need to integrate operation and maintenance procedures with water quality monitoring program, so water quality problems can be fixed as they arise.

### **2.3 Common Data Collection and Monitoring Techniques**

There are several ways to gather water quality data from the distribution system. Utilities can either do grab and/or composite sampling or use online monitors.

Grab and composite samples are good because a sample can be collected anywhere water is available, so sampling sites are almost unlimited. Problems can be small data sets, costs can be high to send collectors to each site and utilities may miss important water quality events due to limited number of samples. Costs may also be high to send the samples to a laboratory to have them analyzed. Some utilities may chose to utilize field test kits to reduce lab costs for on site distribution system monitoring, but the results should be verified occasionally by certified laboratories following OEPA approved test methods.

Online sampling provides a lot of data, which is both a pro and con. This is good because intermittent water quality problems can be detected, but it is bad because it requires a lot of data management. Online monitors are unattended, so personnel costs are generally low. They also provide real-time results for instantaneous operational and regulatory decisions. Some negative aspects of online analyzers are: they need to be sheltered in locations with power and good water flow. Some routine maintenance and consumables are required. They are expensive to purchase, which limits the amount of locations utilities can afford to monitor. There are many types of online monitors: physical (turbidity, particles), inorganic (ph, chlorine), organic (TOC, UV2554, VOCs), biological (algal, protozoan), and flow, level, and pressure.

The most common baseline monitoring parameters are: coliform bacteria, pH, residual chlorine, turbidity, heterotrophic plate count (HPC), DBPs, pressure, temperature, and taste and odor. Chloraminated systems may also monitor for ammonia, nitrite, and nitrate.

### **2.4 Interpreting Water Quality Monitoring Results**

Water quality monitoring programs are used for trending and analysis to ensure that safety, quality, and quantity are not adversely impacted. Also, baseline data helps establish what normal water quality changes may be expected in the distribution system under normal operations.

*Disinfectant residual.* Decrease = stagnation, disruption in treatment, distribution system problems (cross-connection or main break), biofilm growth, or contamination (security breach). Increase = treatment or booster chlorination problems, or change in valve position that may be causing stagnant water elsewhere.

*Turbidity.* System disturbance = main break, cross-connection, fire fighting, flushing, flow reversal, maintenance and repairs, security breach, post precipitation, pump trip.

*pH, conductivity, and alkalinity.* Corrosion control issues, cross connections, treatment problems, security breach, new cement motor linings.

*Volatile Organic Contaminants.* Presence = probable cross-connection.

*Trace metals.* Corrosion control problems, cross-connection.

*Total Organic Carbon.* Increase = biofilm sloughing off, cross-contamination. Decrease = consumption by biofilm, formation of disinfection by-products.

*Water source.* Conductivity is a cheap and easy way to determine water sources in a water system that has multiple water plants feeding into a combined distribution system. Other parameters that can be used are: DBPs, chlorine, fluoride, chloride, nitrate, sulfate, sodium, potassium, total hardness, magnesium, and calcium.

*Tracer studies.* Fluoride can be used to conduct tracer studies in the distribution system as an aid in determining water age, or the hydraulic influences into an area.

*Leak investigations.* Chlorine, fluoride, hardness, alkalinity, pH, conductivity, and DBPs can all be used to determine if a leak is drinking water or from groundwater intrusion.

## **2.5 Additional Reading**

AwwaRF #90798: Guidance Manual for Maintaining Distribution System Water Quality

AwwaRF #90882: Guidance Manual for Monitoring Distribution System Water Quality

AwwaRF #90829: Online Monitoring for Drinking Water Utilities

## **3.0 BIOFILM CONTROL AND ASSESSMENT**

Microorganisms are ubiquitous existing in food, water and air from harsh environments like steam vents on the sea floor to ice covered Antarctica. So it is no surprise that they can be found in water distribution systems on pipe surfaces, tanks, etc. even in the presence of a disinfectant. A working definition of a biofilm is a diverse association of microorganisms and their byproducts existing together. Usually biofilms are made up mostly of bacteria, but fungi, protozoa and other microorganisms have also been associated with biofilms. In addition to the organisms, biofilms are also comprised of dead cells, organic molecules, and inorganic matter that may be trapped among the biomass. In wastewater systems, biofilms can be very thick and slimy and can be observed with the naked eye. In drinking water systems, however, the biofilms are typically very sparse and cannot be detected by look or feel. It is actually very difficult to detect and characterize biofilms in distribution systems and typically the levels and composition of biofilms are not known until the biofilm begins causing problems.

### **3.1 Biofilm Problems**

Typically biofilms are rather benign and do not cause many problems. Sometimes they may even be beneficial by consuming some organic compounds such as haloacetic acids. In some instances, though, the growth of biofilms can lead to problems requiring action on the part of the water utility to control biofilm growth.

The type of organisms in biofilms are usually not a health concern, but under some conditions biofilms can allow the growth of bacteria to a level that will interfere with total coliform tests or the biofilm may support the growth of coliform organisms themselves. Generally, the growth of the coliforms in the biofilm is not of a health concern, but such growth can lead to positive detections in distribution systems even to the point of jeopardizing compliance with the total coliform monthly standard.

Not all biofilm organisms are benign. Pathogens such *Mycobacterium*, *Aeromonas* and *Legionella* can exist in biofilms. It is unclear the extent to which these pathogens can actually grow in the biofilms, but it is evident that the biofilms can shelter these organisms from residual disinfectants. In the environment of a biofilm, dead cells and extracellular “slime” produced by the microbes can react with the chlorine or other disinfectants in the bulk water thereby helping to shelter the organisms from disinfection.

Excess biofilm growth can also produce taste and odor compounds. Some of the fungi associated with the biofilms can produce musty taste and odors and iron reducing bacteria can release sulfur containing compounds and the decay of the dead biomass can also produce objectionable compounds.

Biomass can also accelerate corrosion and the formation of tubercles on iron pipes. Bacterial action can produce an acidic environment within the biomass. This acid can then locally attack the pipe wall which can promote the formation of tubercles. Once these tubercles start to grow, they can shelter the biomass from disinfectants and promote the growth of more biomass.

### **3.2 Sources of Microorganisms**

Although most drinking waters in Ohio are required to add a residual disinfectant such as chlorine, chloramine, or chlorine dioxide, biofilms still survive and grow in distribution systems. The purpose of the disinfection is to make the water safe and potable, not sterile. As a result, small numbers of bacteria and other microbes can pass through the treatment plant, through the disinfection process, and into the distribution system. Once in the distribution system these microbes can attach to the walls of pipes, valves, tanks, etc. There these microbes feed off of the trace levels of nutrients (TOC, nitrate, phosphorus containing compounds, etc.) and grow and multiply usually at a very slow rate.

Microbes can also enter the distribution system during construction, through pipe breaks, cross connections, or any other opening in the pipe system. Regardless of the source of the contamination, the small amount of microbes that survive the residual disinfectant act as a seed for growth. As the biofilm grows, cells from a particular biofilm can shear off, enter the bulk water, and be transported down a pipe to act as a seed in another location.

### **3.3 Biofilm Growth**

All of the factors that may influence the amount, composition, and location of biofilms are not understood. Many factors exist and the interaction of these factors can affect different biofilms differently. The difficulty in predicting biofilm growth is compounded by the fact that different biofilms can exist in different areas of the same distribution system and in fact different biofilms

can be detected within the same pipe. Despite these complexities, however, there are some general factors that seem to influence the growth and composition of a biofilm. The general factors that seem to influence biofilm growth are discussed below.

*Seed.* The composition of the biofilm is of course determined by the type of organisms that are present initially to begin the biofilm growth. If good disinfection practices are followed in treatment, main construction and repair, etc. then the opportunity for undesirable organisms to enter the system are reduced. In addition, the growth of biofilm elsewhere in the distribution system can act as a seed to establish biofilm elsewhere.

*Food.* For most biofilms, the availability of nutrients is the key factor limiting growth. In drinking water systems, the organic carbon in particular seems to be the limiting nutrient. Systems with higher TOC have been shown to support more growth than systems with low TOC.

*Disinfectant.* Most disinfectants are rather effective in killing the organisms that compose a biofilm provided that the disinfectant will come in contact with the organisms. However, the dead cells, extracellular molecules, and other components of a biofilm react with disinfectants to limit their contact with biofilm organisms. In the absence of a disinfectant, or in cases where the disinfectant is used up before contact with the organisms, biofilm growth will not be limited by disinfectants.

The type of disinfectant can also affect biofilm growth. In some instances, the use of chloramines yields better biofilm control. The reason for this may be that since chloramines are less reactive than free chlorine, chloramines can penetrate deeper into the biofilm before it is depleted.

*Hydraulics.* The flow velocity appears to have an affect on biofilm accumulation. In general, low flow conditions tend to favor formation of biofilms. It may be that higher flow is more successful in keeping a disinfectant residual near the biofilm or that higher flows impose a sheer stress on the biofilm which will limit biofilm thickness.

*Temperature.* Higher temperatures tend to favor the development of a biofilm. This is true not only for the amount of organisms present, but also for the diversity of the biofilm.

*Pipe condition and material.* In general, pipes that have significant corrosion are more supportive of biofilm growth than non-corroded pipes. Presumably, the corrosion deposits, tubercles, minute cracks, etc. act as a shelter for the biofilm helping to protect the organisms from a disinfectant.

### **3.4 Biofilm Control**

Given that small quantities of microorganisms are always present in the water from treatment or are introduced through very minute contamination pathways, successful biofilm control measures are based on limiting growth or implementing measures to reduce established growth. The paragraphs below outline some biofilm control measures that have proven to be successful in drinking water systems. Successful control of biofilms usually relies on a combination of several of these factors and is highly system dependent.

*Decrease nutrients.* Decreasing the food source of the microorganisms is probably the control measure with the highest probability of success. Without a food source, the biofilm organism will not grow. As mentioned above, TOC, specifically the biodegradable fraction of TOC, is usually the limiting nutrient in drinking water systems. Systems have several options to reduce the TOC at the treatment plant. Enhanced coagulation, activated carbon, source water protection and other technologies have all been successful in reducing TOC. Another option may be instead of reducing overall TOC, to remove primarily the fraction of TOC that can be eaten by microorganisms. Many systems do this by moving their point of disinfection to after the filtration process. This allows bacteria to grow in the filter media and these bacteria then eats much of the TOC so the final water will have a lower nutrient content.

In some systems, nitrogen may be the limiting factor. Ammonia, nitrate or nitrite removal technologies used at the plant can reduce this food source. For systems using chloramines, careful control of ammonia addition will help to eliminate free ammonia in the finished water.

*Corrosion control.* Optimizing corrosion control practices to minimize iron corrosion can also be a successful biofilm minimization strategy. This is especially useful for systems with pipes that are not already heavily encrusted with iron tubercles. As discussed above, the corrosion deposits, tubercles, etc. can act as a shelter to help protect the biofilm from a disinfectant. In moderate to severely corroded iron pipes, the iron can be a significant sink for chlorine. So much so that little or no chlorine may exist in areas with corroded pipes and the chlorine that may be in the bulk water will be depleted near the pipe surfaces.

*Establishing a disinfectant or raising a disinfectant dose.* The presence of a disinfectant can be a very effective means of controlling biofilms. The disinfectant though, must be at such a level that it can penetrate into the biofilm and attack the organisms directly. One way to accomplish this is to raise the disinfectant dose high enough to overcome the demand exerted by the pipe. In many instances, though, the pipe demand is such that it would not be practical to overcome by raising the disinfectant residual. Therefore this approach will be most successful when coupled with improving corrosion control or a good flushing program. Another means would be to eliminate stagnant water areas. As the water stagnates, the disinfectant residual continues to decrease and becomes less effective in controlling biofilm. By keeping fresh water moving through the system, water containing higher levels of disinfectant is brought in and may be effective in controlling growth.

*Flushing.* Flushing of the distribution system can help control biofilms in several ways. Flushing can physically remove some of the biofilm by scouring action. Flushing can remove accumulated debris and corrosion products that shield the biofilm from disinfection. It can also bring fresh water in with a disinfectant residual that can then attack the attached biofilm. It is important to remember, though, that flushing is only a temporary solution and unless the conditions which support biofilm growth are addressed, the biofilm will eventually return to original problematic levels.

### **3.5 Conclusions**

Biofilms are a very complex interaction of microorganisms that are not very well understood. They exist in every drinking water systems. Most of the time they do not cause a problem but a combination of factors can sometimes lead to their development and proliferation to such a point

in which they can cause water quality, health, and corrosion issues. Control of a problematic biofilm can be difficult with the solution usually found in changing the underlying conditions that contribute to their development.

### 3.6 Additional Reading

*Influence of Distribution System Infrastructure on Bacterial Regrowth.* 2003. J. Clement, et al. AwwaRF report no. 2523.

*Pathogens in Model Distribution Systems.* 1998. A.K. Camper, et al. AwwaRF report no. 936.

*Factors Limiting Microbial Growth in Distribution Systems: Laboratory and Pilot Scale Experiments.* 1996. A.K. Camper. AwwaRF report no. 704.

*Assessing and Controlling Regrowth in Distribution Systems.* 1990. LeChavallier, et al. AwwaRF Report No. 309.

*Bacterial Regrowth in Distribution Systems.* 1988. W.G. Characklis. AwwaRF Report No. 101.

*Factors Affecting Microbial Growth in Model Distribution Systems.* 2000. A.K. Camper, W.L. Jones. AwwaRF Report No. 183.

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“Comparing Chlorination and Chloramination for Controlling Bacterial Regrowth.” Neden, D.G. et al. *Journal AWWA* . Vol. 84 Iss. 7. July 1992. Page(s) 80-88.

“Assimilable Organic Carbon as an Indicator of Bacterial Regrowth” van der Kooij, D. *Journal AWWA* . Vol. 84 Iss. 2. February 1992. Page(s) 57-65.

“Association of Microorganisms With Surfaces in Distribution Systems” Herson, D.S. et al. *Journal AWWA* . Vol. 83 Iss. 7. July 1991. Page(s) 103-106.

“Analyzing Biofilm Processes Used in Biological Filtration” Rittmann, B.E. et al. *Journal AWWA* . Vol. 82 Iss. 12. December 1990. Page(s) 62-66.

“Disinfecting Biofilms in a Model Distribution System” LeChevallier, M.W. et al. *Journal AWWA* . Vol. 82 Iss. 7. July 1990. Page(s) 87-99.

“Achieving Biologically Stable Drinking Water” Rittmann, B.E., Snoeyink, V.L. *Journal AWWA* . Vol. 76 Iss. 10. October 1984. Page(s) 106-114.

## 4.0 DISTRIBUTION SYSTEM PIPING AND STORAGE

### 4.1 Distribution Storage Facilities

Poor mixing and inadequate volume turnover in storage facilities can result in significant increases in water age, depletion of the disinfectant residual, increased microbial counts, increased DBP concentrations, and nitrification (in chloraminated distribution systems). For tanks that “float” on the system, that is, the level in the tank rises and falls with system pressure, it is possible that water quality degradation can go undetected for an extended period of time before water from the upper portion of the tank is discharged to the distribution system. Not only can this result in distribution of water of generally poor quality (e.g., high DBP concentrations) and jeopardize compliance with state and federal drinking water regulations, but may result in a spread of nitrification to other portions of the distribution system in chloraminated systems.

#### 4.1.1 Evaluating Storage Facility Mixing Characteristics

*Desktop evaluations of tank mixing.* Desktop theoretical evaluations of hydraulic residence time, inlet momentum, fill time, and volume turnover can be used to predict mixing characteristics of a storage tank. An AwwaRF report entitled *Water Quality Modeling of Distribution System Storage Facilities* (Grayman, et al., 2000) provides an overview of these factors, their importance in mixing efficacy, and examples of how to evaluate their impact on storage tank mixing characteristics.

There are two basic flow patterns in storage facilities: plug flow and mixed flow. However, most storage facilities have not been designed to operate in either plug or completely mixed flow and generally operate somewhere in between the two (Kirmeyer, et al., 1999). For storage facilities presumed to be operating under mixed flow conditions, the following equation can be used to estimate the hydraulic residence time. Equations for tanks presumed to be operating under plug flow conditions, as well as more complicated equations for mixed conditions are available in *Water Quality Modeling of Distribution System Storage Facilities*.

$$HRT_{avg} = \left[ \frac{V_{max}}{V_{max} - V_{min}} \right] \div N$$

Where:  $HRT_{avg}$  = average hydraulic residence time  
 $V_{max}$  = average maximum tank level  
 $V_{min}$  = average minimum tank level  
 $N$  = number of drain/fill cycles per day

The inlet momentum (inlet velocity  $\times$  flow rate) also has a significant impact on tank mixing. Generally, increased momentum results in better mixing performance. While there is no standard target value to achieve good mixing for inlet momentum, inlet momentum has a significant impact on the mixing time required to achieve good mixing.

The theoretical mixing time in a cylindrical storage tank is a function of the tank volume at the start of the fill cycle, the inlet diameter, and the inlet momentum. The following equation can be used to calculate the theoretical mixing time (Grayman, et al., 2000).

$$TMT = 9V^{2/3} \left( \frac{d}{Q} \right)$$

Where:  $TMT$  = theoretical mixing time  
 $V$  = tank volume at start of fill cycle

$d$  = inlet diameter

$Q$  = inflow rate

To achieve good mixing, the actual fill time should be greater than the theoretical mixing time. Therefore, the previous equations can be restated in terms of the required change in water volume during the fill cycle as a fraction of the volume at the start of the fill cycle. If the following condition is met, the fill time is adequate to achieve good mixing. (Note that this does not account for individual tank flow patterns and is only an assessment of the fill characteristics.)

$$\Delta V / V > 9d / V^{1/3}$$

Where:  $\Delta V$  = change in water volume during fill period

$V$  = tank volume at start of fill cycle

$d$  = inlet diameter

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. Kirmeyer, et al. (1999) recommended a minimum turnover of 3 to 5 days (20 to 33 percent turnover per day). The percent of volume ( $\Delta V/V \times 100$ ) that must be exchanged can be calculated using the previous equation. In a well-mixed storage facility, the turnover, expressed in days, is equivalent to the average hydraulic residence time.

*Using water quality data to evaluate storage tank mixing.* Water quality monitoring can also be a valuable tool in assessing mixing characteristics of a storage tank. Disinfectant residual data, DBP data, temperature data, and bacteria counts can effectively demonstrate whether a storage tank is being mixed effectively. These data can be particularly effective when compared to tank level data and evaluations of tank turnover. Continuous temperature monitoring, in particular, can help to evaluate mixing characteristics, and is discussed in detail in the next section.

To illustrate the manner in which water quality can assist in assessing tank mixing, **Table 1** presents total chlorine, TTHM, and HAA5 concentrations the top and bottom of five tanks. Utilities attempting to complete similar evaluations should also consider including HPC and temperature monitoring as a part of the evaluation. Each tank in **Table 1** has a common inlet/outlet located at the bottom of the tank.

**Table 1. Use of Water Quality to Characterize Tank Mixing**

Tank No.	Temperature (° F)		Free Chlorine (mg/L Cl <sub>2</sub> )		TTHM (µg/L)		HAA5 (µg/L)	
	Top of Tank	Bottom of Tank	Top of Tank	Bottom of Tank	Top of Tank	Bottom of Tank	Top of Tank	Bottom of Tank
1	80	79	0.8	2.0	75	54	42	20
2	78	78	0.2	1.8	78	58	35	41
3	81	78	0.0	1.9	74	56	12	44
4	81	80	0.0	1.7	66	69	25	51
5	81	78	0.0	1.9	74	50	22	47

Each tank of the tanks in Table 1 is also poorly mixed, as evidenced by the difference in free

chlorine concentrations at the top and bottom of the tank, but each has a different associated water quality problem.

- Tank 1 Temperature is essentially the same at both the top and bottom of the tank. The tank has a relatively high free chlorine concentration at the top of the tank. However, because of the increased water age both TTHM and HAA5 concentrations are higher in the upper part of the tank.
- Tank 2 Temperature is the same at both the top and bottom of the tank. Free chlorine concentration is relatively low at the top of the tank. TTHM concentration is higher in the top of the tank. HAA5 concentration is consistent indicating HAA5 formation has stopped, or, more likely, the early stages of biodegradation of HAA5.
- Tank 3 There is a 3 degree temperature difference between the top and bottom of the tank, which is quite substantial and indicative of stratification. Like Tank 2, TTHM concentration has increased in the top of the tank, but biodegradation of HAA5 has clearly begun.
- Tank 4 Based on temperature and TTHM data, it would appear the tank is well mixed. However, the differences in free chlorine and HAA5 concentrations indicate otherwise. This demonstrates the importance of looking at multiple parameters when evaluating mixing in storage tanks.
- Tank 5 Again, there is a substantial (3 degree) temperature difference between the top and bottom of the tank indicating thermal stratification. TTHM levels are much higher at the top of the tank, no chlorine residual exists in the top of the tank, and HAA5 biodegradation has begun.

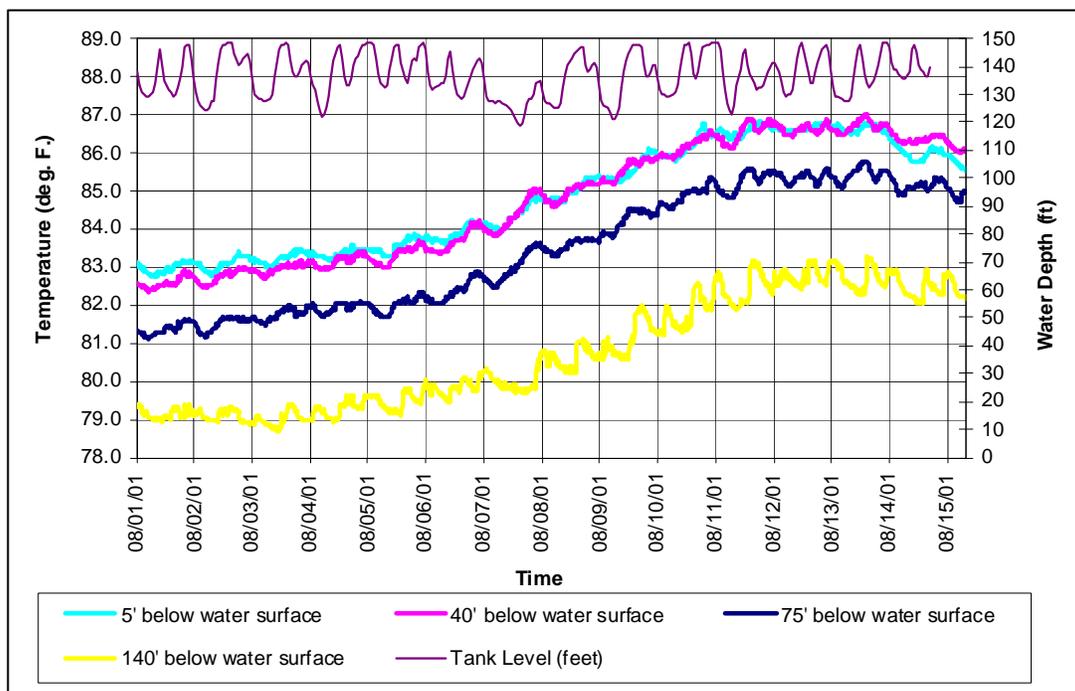
**Table 1** shows one example of using water quality data to evaluate tank mixing. It is also important to note that, when left unchecked, poorly mixed storage facilities are potential sources of nitrification in chloraminated distribution systems. In such cases, other parameters, such as nitrate, nitrite, HPC, and total coliform can be used in a similar manner.

*Using temperature profiles to characterize tank mixing.* Temperature measurements taken inside a storage tank can also be an effective tool in evaluating the water mixing characteristics of the tank. This can be done relatively inexpensively using a data logging device and thermistors spaced at the appropriate distance and lowered into the tank from a top access hatch. A temperature profile can be developed by continually measuring the water temperature at various depths in a tank over the course of several days. The temperature profile can then be compared against tank water level data to determine the effectiveness of mixing and the presence of, or potential for, thermal stratification in the tank.

**Figure 1** presents the results of temperature monitoring in a poorly mixed standpipe (Mahmood, et al., 2003). The temperature difference between the probes at 5 feet and 40 feet below the water surface was minimal. However, the temperature at those depths was consistently higher (approximately 1°F) than the temperature at 75 feet below the water surface. The temperature at 75 feet below the surface was also consistently higher (generally more than 2 °F) than the temperature at 140 feet below the water surface. The difference in temperature between the top

and bottom of the storage tank was generally between 3.5 and 4 °F.

**Figure 1. Temperature Profile of a Poorly Mixed Storage Tank**

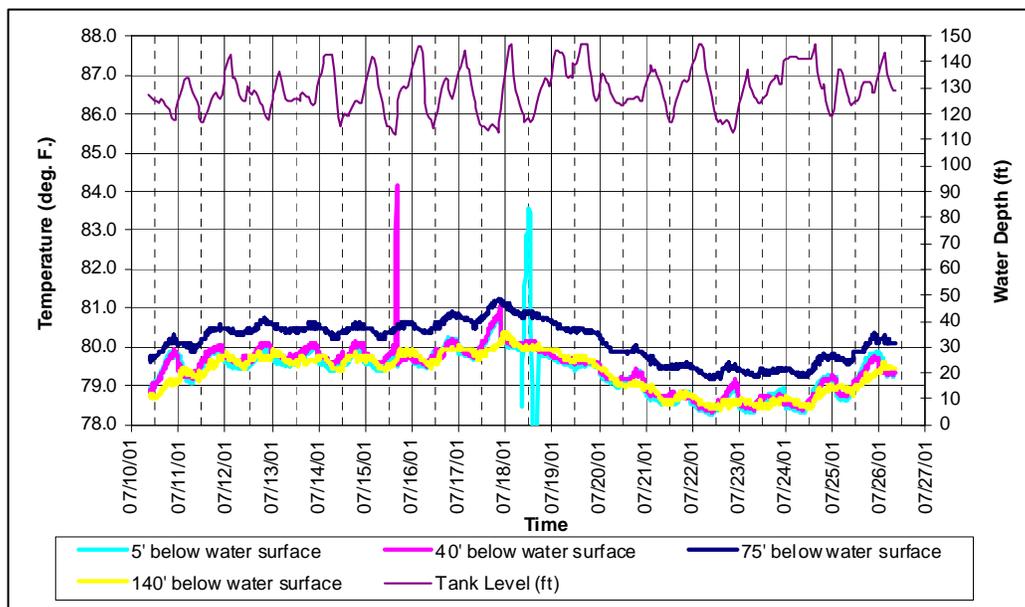


Source: Mahmood, et al., 2003

From **Figure 1**, it can also be seen that the temperatures at the different depths showed very little convergence during the tank filling cycles. More notably, as the tank refilled each evening and the water temperature at the bottom of the tank decreased there usually was no corresponding decrease in water temperature at the top of the tank. This implies that the fill cycle failed to mix the water throughout the full depth of the tank.

**Figure 2** presents the results of temperature monitoring in a well-mixed tank (Mahmood, et al., 2003). The water temperatures at 5 feet, 40 feet, and 140 feet below the water surface were consistently similar. The authors noted a poorly calibrated temperature probe resulted in inaccurate measurements for the probe located 75 feet below the water surface. On two occasions, the temperature 5 feet and 40 feet below the water surface were drastically higher than the temperatures at other depths in the tank. It was determined that on those days, the water level in the tank dropped sufficiently that the probes were measuring ambient air temperature.

**Figure 2. Temperature Profile of a Well-Mixed Storage Tank**



Source: Mahmood, et al., 2003

From **Figure 2**, it can be seen that the maximum temperature difference between the top and bottom portions of the tank was less than 1°F, and lasted for only a few hours. The data indicate that although a slight stratification typically begins to occur each day, as seen by the slight increase in the difference in recorded temperature between the top and bottom of the tank, these temperatures converge, when the tank is refilled. This convergence of the temperatures indicates that water in the tank is adequately mixed during the tank filling period

*Computational fluid dynamic modeling.* While desktop evaluations, water quality data, and temperature measurements can be used to quantitatively describe mixing characteristics, computational fluid dynamic (CFD) modeling can describe mixing characteristics qualitatively by providing visual images of water mixing inside a tank. CFD modeling can also be used to effectively evaluate the impact of design changes on mixing characteristics.

CFD software packages can be expensive and are not necessary to evaluate storage tank mixing characteristics. However, AWWARF has released a special-purpose CFD package, HydroTank, solely for evaluating storage tank mixing. The package is available as a part of the AwwaRF report *Water Quality Modeling of Distribution System Storage Facilities* (Grayman, et al., 2000). That report also includes a detailed discussion of CFD modeling and its applicability to evaluating storage tank mixing characteristics.

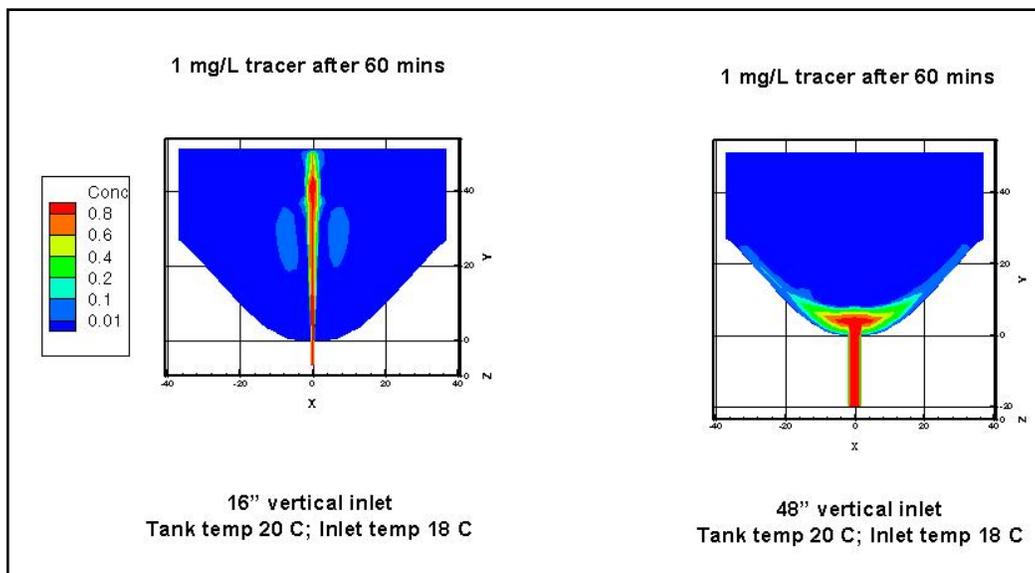
#### **4.1.2 Increasing Inlet Momentum**

Inlet momentum (velocity  $\times$  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 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 3** shows the impact of inlet momentum on tank mixing.

As previously mentioned, the inlet momentum is the product of the inlet velocity and flow rate. The inflow rate is the same for both tanks in **Figure 3**. The inlet velocity is equivalent to the inflow rate divided by the area of the inlet. The tank with the smaller diameter inlet has a smaller area, and consequently a higher inlet velocity. As a result, the tank with the smaller inlet diameter also has a greater inlet momentum than the tank with the larger diameter. From the figure, it can be seen that the flow in the tank with the smaller diameter inlet reaches the upper levels of the storage tank. In the tank with the larger diameter inlet, the inflow hovers near the bottom of the tank. Therefore, another way to increase inlet momentum and improve tank mixing, rather than increasing the inflow rate, is to reduce the inlet diameter.

**Figure 3. Effect of Inlet Momentum on Tank Mixing**



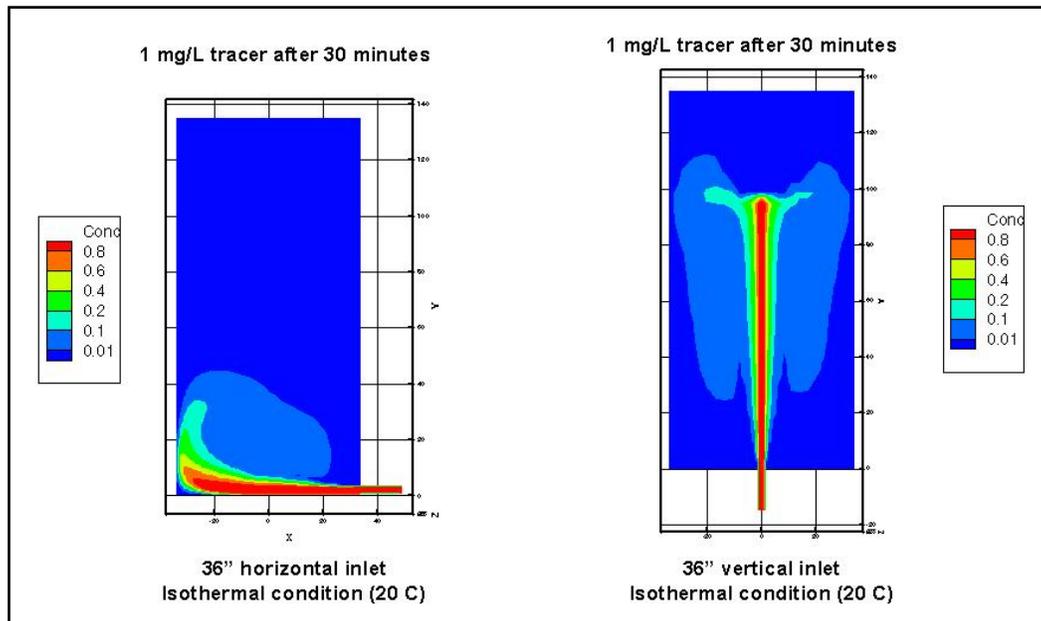
#### 4.1.3 Optimizing Inlet Location and Orientation

Mixing requires a source of energy. In distribution system storage tanks, this energy is normally introduced during tank filling. As water enters a tank, a jet is formed and the water present in the tank is drawn into the jet. Circulation patterns are formed that result in mixing. The path of the jet must be long enough to allow the mixing process to develop for efficient mixing to occur. Therefore, the inlet jet should be directed away from any obstacles, such as a tank wall, the bottom of the tank, or deflectors (Grayman, et al., 2000). The degree and speed of mixing depends primarily upon the size of the tank and the momentum of the incoming jet.

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. Under such a scenario, nitrification may occur in the older water stagnating at the top of the tank.

**Figure 4** demonstrates the impact of inlet location and orientation on tank mixing. In the tank on the left, the inlet is located horizontally along the bottom of the storage tank. During filling, the water jet hits the vertical wall on the opposite side of the tank, resulting in a loss of inlet momentum, causing the inflow to remain near the bottom of the tank. When the inlet is vertically oriented, in the center of the bottom of the tank, under identical flow conditions, the water jet reaches the upper levels of the tank resulting in more effective mixing. For tanks with horizontal inlets located at the bottom of the tank, extending the inlet to the center of the tank, and installing an elbow to direct the jet upward can improve tank mixing.

**Figure 4. Impact of Inlet Location and Orientation on Tank Mixing**



#### 4.1.4 Avoid Baffling in Distribution Storage Tanks

Baffles are used in storage tanks to encourage plug flow, and are often used in contact basins to eliminate short-circuiting and dead zones. In large ground distribution storage tanks, in which the configuration is such that it is very difficult to achieve good mixing, baffles may also be used to eliminate stagnant areas in the tank; however, Grayman, et al. (2000) noted that under plug flow conditions, disinfectant residual decay is generally greater in distribution system storage tanks compared to well-mixed storage facilities. By encouraging plug flow, baffles essentially result in increased water age of water leaving distribution storage facilities, whereas in well mixed tanks the water age leaving the tank is the average of the water contained in the tank and is generally lower than that in plug flow conditions. Consequently, baffles should generally be avoided in distribution system storage facilities to aid in maintaining a disinfectant residual, minimizing DBPs, and avoiding nitrification.

#### 4.1.5 Decommissioning Excess Storage

Historically, distribution system storage tanks have generally been built to provide adequate pressures, fire flow, and peak demand capabilities. Quite often the tanks have also been

designed to accommodate future growth and long-term water system needs. Therefore, some distribution system storage tanks may be oversized. Storage tanks may also be hydraulically locked out of the distribution system due to high system pressures, low system demands, and inadequate height of the tanks. Oversized tanks and/or hydraulically locked out tanks do not have adequate flow through the tanks and volume turnover, potentially resulting in water quality degradation. When events such as main breaks, fire flow, or some other unexpected peak demand condition occurs in a system, water from these tanks can be drawn into the distribution system.

For a tank that is oversized or hydraulically locked out under normal system operating conditions, there are limited options for improving mixing characteristics and reducing water age. For a tank that is hydraulically locked, the maximum water level in the tank can be lowered to reduce the operational hydraulic grade. Similarly, the tank can be raised, effectively lowering the maximum water level. For an oversized tank, more water needs to be forced in and out of the tank on a daily basis, possibly by adjusting pumping schedules. Quite frequently, such modifications may not be feasible due to system hydraulics. Therefore, for an oversized or hydraulically locked out tank, permanent decommissioning of the tank can be considered to prevent water quality degradation. Before a tank is decommissioned, the effects of taking the tank out of service should be determined. A distribution system analysis should be performed to make sure that the tank is not needed and there is adequate hydraulic connectivity for equalization storage, fire flow, or emergency conditions such as main breaks or treatment plant shutdowns.

When it is necessary to maintain a storage facility due to consumer demand, fire flow, or hydraulic considerations it may be necessary install pumps to force water from the tank and encourage effective mixing and volume turnover.

## **4.2 Distribution Piping**

Distribution system piping configuration and materials can have a significant impact on water quality – primarily as a result of excessive water age. High water age in the distribution pipes can lead to a number of water quality problems including loss of disinfectant residual, increased DBP concentrations, taste and odor, color, increased microbial activity, and nitrification (in chloraminated distribution systems). Piping material can also have a significant impact on water quality. For example, unlined cast iron pipe may exert substantial disinfectant residual demand, metals may leach from cement mortar linings, and corrosion of metal pipe may result in increased metals concentrations, taste and odor, color, or other water quality problems.

### **4.2.1 Looping Dead-Ends**

Excessive water age at dead ends can be reduced with pipe looping which generally involves constructing new pipe sections to make appropriate hydraulic connections among existing pipes. However, in some cases pipe looping can also create zones with very slow moving water elsewhere in the system. For example, looping a dead end may cause water with opposite flow directions and similar flow rates to meet and cause very slow moving water at that location. Therefore, the specific hydraulic response of a system to looping must be assessed to make sure that looping does not negatively impact the residence time of other parts of the system.

## 4.2.2 Managing Valves

Intentional or unintentional closed valves in a distribution system may create stagnant water leading to degradation of water quality in those locations. The presence of unintentional closed valves could be due to some valves being inadvertently turned in the wrong direction or being broken. These valves may remain undetected due to poor record keeping and buried or paved-over valve boxes. A comprehensive valve inventory and maintenance program is necessary to identify the location and status of valves in a system. A valve exercise program is also necessary to determine improperly positioned and broken valves. As these valves are discovered, their position can be corrected or they can be replaced to minimize stagnant water zones and associated high water age in distribution system pipes.

## 4.2.3 Automatic Flushing and Blow-Offs

Automatic flushing and blow-offs (**Figure 5**) can be used to eliminate dead ends and stagnant water zones that have high water age. These devices induce continuous or automatic intermittent flow of water designed to remove old water from dead-end or stagnant zones and pull fresher water into these locations from other areas. The velocities for a blow-off are generally insufficient ( $< 2.5$  feet/sec) to remove sediments or biofilm. Continuous or automatic intermittent blow-offs can be used on a seasonal basis when DBP peaks are more likely to occur, for example, during high water temperature periods. The need for and appropriate locations of blow-offs can be determined from distribution system historical records because high water age locations that result in low disinfectant residuals, high DBP concentrations, high heterotrophic plate counts (HPCs), coliforms or nuisance bacteria (fecal coliforms are not a result of water age or regrowth, they are an indicator of contamination).

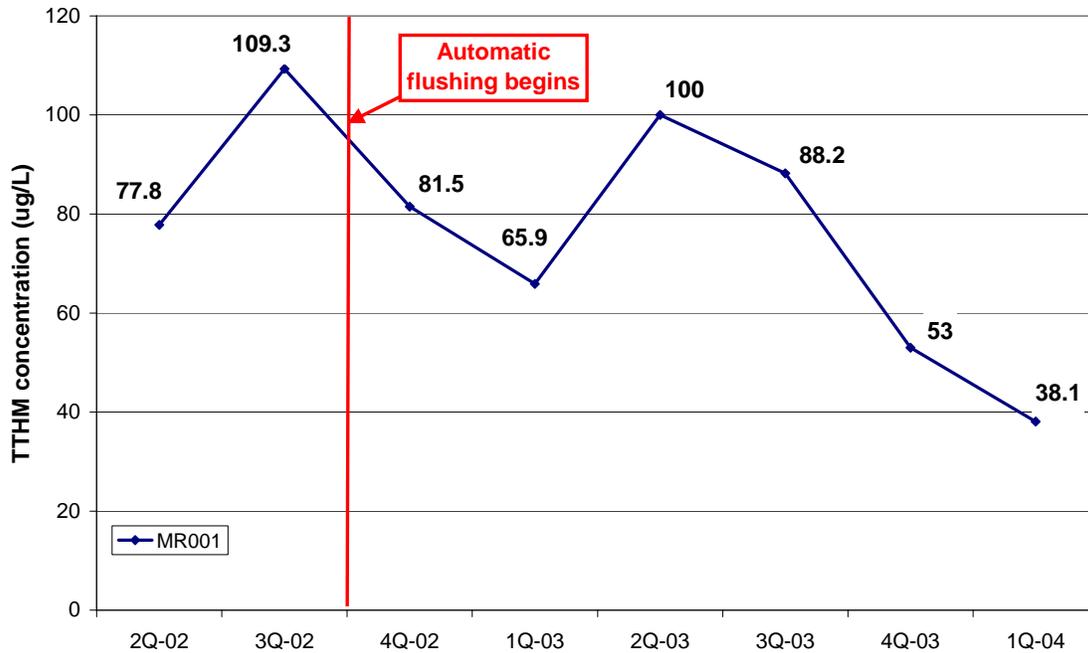
**Figure 5. Typical Automatic Flushing Device.**



*Photo courtesy of Hydro-Guard International.*

**Figure 6** shows the impact of automatic flushing on distribution TTHM concentrations for one system in Ohio. The results presented are for the maximum residence time location (which is the only area of the system in which the flushing devices were installed). As shown, automatic flushing resulted in approximately a 20-30  $\mu\text{g/L}$  decrease in TTHM concentrations from the year prior to installation of the device. The devices themselves are relatively inexpensive, costing approximately \$2,500. Water loss and disposal of flushed water must be considered prior to implementation of such a device, however this may be a cost effective approach to address DBP or other water quality issues resulting from excessive water age in the distribution system.

**Figure 6. Impact of Automatic Flushing on Distribution TTHM Concentrations**



#### **4.2.4 Replacing Oversized Pipes**

In portions of a distribution system where pipes are oversized, the water velocity is lower and therefore hydraulic residence times are longer than necessary causing high DBP levels. Areas of a distribution system that have been abandoned or have experienced negative demand growth over many years may contain oversized pipes, causing excessive hydraulic residence time. Where appropriate, the pipe sizes in these areas can be reduced or sections of pipes can be valved off if they are no longer needed to reduce the residence time of water. However, the effect of replacing or valving oversized pipes on downstream areas should be evaluated to make sure that such modifications will not cause hydraulic constrictions for the downstream areas.

#### **4.2.5 Other Considerations**

It is important to note that improving mixing in storage facilities can result in a reduction in distributed water quality. In poorly mixed tanks, in which the actual volume of the tank being used (e.g., only the bottom third of the tank), the water age of the water being distributed can be relatively low which may be indicated by good disinfectant residuals and relatively low DBP concentrations. However, when demand conditions result in water being withdrawn from the top two-thirds of that same tank, there may be no remaining disinfectant residual and DBP concentrations can be quite high. When the full volume of the tank is used (i.e., when the tank is completely mixed or near completely mixed), the average age of distributed water will be higher than when only the bottom third of the tank is used and utilities may notice a decrease in distributed water disinfectant residuals or slight increases in DBP concentrations; however, the average overall quality of the water in the tank will be better and the quality of water discharged from the tank will be more consistent. That is, under conditions when the tank drawdown is more significant than under normal operations, it is not likely that utilities would see drastically different residual or DBP concentrations in water discharged compared to normal operations.

It is also worth noting, that poor quality in a storage tank is not necessarily indicative of poor mixing. A utility may use the desktop evaluation tools discussed in this paper and find that a particular tank should be well mixed. In some cases, it could be that the distribution system configuration is such that the water entering the tank is of poor quality to begin with. Fresh water might not be making it to the tank at all or in limited amounts so the tank is not turning over with fresh water. In such a case, the system may simply be just pushing older water around and improvements to tank mixing and turnover will have no impact on water quality. Increased water quality monitoring, including the use of on-line monitors, and modeling can help to identify when this is occurring and identify hydraulic solutions.

### 4.3 Impacts of Distribution System Materials

Aging pipes and pipe materials can have significant water quality impacts due to the because of the presence of corrosion byproducts, biofilms, and sediment deposits in the pipes (see **Table 2**). Systems can reduce localized water quality decay and thus improve water quality through cleaning-and-lining or replacement of pipes, and through periodic flushing programs. The selection of any specific method depends on water quality data, hydraulic condition, pipe condition, and economic factors.

**Table 2. Potential Water Quality Impacts of Different Distribution Piping Materials**

Pipe Material	Potential Water Quality Impacts
Cast iron	<ul style="list-style-type: none"> <li>• May exert higher disinfectant demand.</li> <li>• Loss of disinfectant residual.</li> <li>• Increased DBP concentrations due to need for higher disinfectant dose to overcome higher disinfectant demand.</li> <li>• Color (red water).</li> <li>• Taste and odor.</li> <li>• Increased microbial activity.</li> <li>• Nitrification.</li> </ul>
Ductile-iron (cement mortar-lined)	<ul style="list-style-type: none"> <li>• Lack of adequate quality control during manufacturing may lead to increased metals concentrations, including barium, cadmium, chromium, or aluminum.</li> </ul>
Asbestos-Cement	<ul style="list-style-type: none"> <li>• Increased asbestos, barium, cadmium, chromium, or aluminum.</li> </ul>
Pre-stress Concrete Cylinder	<ul style="list-style-type: none"> <li>• Leaching of calcium in non-stable waters.</li> <li>• Lack of adequate quality control during manufacturing may lead to increased metals concentrations, including barium, cadmium, chromium, or aluminum.</li> </ul>
Lead	<ul style="list-style-type: none"> <li>• Can contribute to increased tap lead concentrations under certain water quality conditions.</li> </ul>
Copper	<ul style="list-style-type: none"> <li>• May contribute to increased tap copper concentrations under certain water quality conditions.</li> <li>• Susceptible to microbially-influenced corrosion depending on installation and other water quality conditions.</li> <li>• Pitting corrosion may result in home plumbing failures.</li> </ul>
Galvanized	<ul style="list-style-type: none"> <li>• Increased zinc, iron, lead, copper, cadmium, chromium,</li> </ul>

	aluminum, barium, or other metals concentrations.
Plastic (HDPE)	<ul style="list-style-type: none"> <li>• May result in increased leaching of volatile organic chemicals in surrounding soils.</li> </ul>

For a water distribution system, water quality degradation due to pipe corrosion, biofilm, and sediment deposition is most prevalent in unlined cast iron pipes. Problems can be minimized by cleaning-and-lining or replacement of aging unlined cast iron pipes. Pipe replacement may be the preferred option if a pipeline has structural problems or there is a need to increase hydraulic capacity with a larger diameter pipe. If a pipeline is structurally sound, then pipe cleaning is a less expensive option, but for unlined cast iron pipes, pipe lining may also be necessary to achieve a permanent improvement and prevent a recurrence of the problem. Alternative pipe cleaning methods include high pressure sand blasting, mechanical scappers, pigging, swabbing, flow-jetting, and chemical cleaning. Among the more common lining materials are cement-mortar, asphalt (bituminous), epoxy resins, rubber, and calcite. Cement is most commonly used pipe lining method, although several types of degradation of cement material can occur in the presence of acidic waters or waters that are aggressive to calcium carbonate (e.g. soft waters). For example, soft waters can progressively hydrolize calcium silicates constituents of concrete into silica gels producing soft surfaces, and leach calcium hydroxide from the cement lining (AWWA, 2002).

#### 4.4 System Expansion Alternatives

As communities grow, the need to expand the water service area is a necessity. However, the manner in which a system expands can have significant impacts on distributed water quality. Installing large diameter transmission mains and storage facilities to serve build-out capacity can substantially increase water age. For this reason it is recommended that utilities consider using smaller planning horizons (five to ten years) when adding distribution system infrastructure. Installing two smaller distribution mains – one now and one in the future – rather than a single larger main can help to maintain or even improve distributed water quality. The use of dual or parallel storage tanks (e.g. two 1-million gallon tanks) as opposed to a single large tank (e.g., one 2-million gallon tank) can have similar impacts on water quality. Similarly, replacement of oversized existing mains (Section 4.2.4) with smaller mains or decommission of excess storage (Section 4.1.5) can help to reduce water age and improve water quality.

The use of smaller mains – either as a part of a phased expansion or simply to reduce water age – is not without hydraulic and economic impacts. The use of a single, smaller main may be less expensive than a larger main from a capital cost perspective, but will induce additional head loss in the system potentially requiring higher horsepower pumps and increasing operating costs. Over the long-term, the use of two smaller mains is also likely to cost more than the installation of single, larger main – both from a capital and maintenance cost perspective. These factors should be weighed when considering expansion.

#### 4.5 Additional Reading

AwwaRF, *Development of Distribution Water Quality Optimization Plans*  
 AwwaRF, *Distribution Water Quality Changes Following Corrosion Control Strategies*

*AwwaRF, Guidance Manual for Maintaining Distribution Water Quality*  
*AwwaRF, Guidance for Management of Distribution Systems Operation and Maintenance*  
*AwwaRF, Maintaining Water Quality in Finished Water Storage Facilities*  
*AwwaRF, Assessment of Existing and Developing Water Main Rehabilitation Practices*  
*AwwaRF, Water Quality Modeling of Distribution System Storage Facilities*  
*AwwaRF and DVGW, Internal Corrosion of Water Distribution Systems*  
*AWWA G200, Distribution Systems Operation and Management*  
*AWWA, Manual of Water Supply Practices M56, Fundamentals and Control of Nitrification in Chloraminated Drinking Water Distribution Systems*  
*AWWA, Manual of Water Supply Practices M 58, Assessment and Control of Corrosion and Metals Release in Drinking Water Distribution Systems (in progress)*  
*USEPA, Operational Evaluation Guidance Manual (in progress)*

## **5.0 FLUSHING PROGRAMS**

There are many reasons for flushing water distribution systems. Flushing is performed in response to customer water quality complaints, discolored water, sediment removal, taste and odor control, reduction of turbidity, low chlorine residuals, bacterial growths or biofilms, to reduce water age and TTHMs and HAAs, and to reduce corrosion byproducts. Deterioration of water quality in the distribution system depends on a variety of factors, including detention time or water age, proximity to dead end mains or low flow conditions, pipe material and condition, flow velocities, season and temperature effects, microbiology of the water, and the source of supply. The flushing protocol will depend on the objectives and water quality issues.

In designing a flushing program, a utility should analyze customer water quality complaints and routine data such as chlorine, TTHMs, and HAA5s. Water quality data collected during a flushing program should emphasize time series data for carefully selected locations. Non-routine sampling sites may be required to properly represent the system and flushing program objectives.

The decision to flush is most often made in response to customer complaints. A proactive program is desirable so that water distribution water quality issues are addressed in advance of impacting the customer. While basic programs normally just respond to complaints, more complex programs use water quality monitoring data to set the flushing frequencies to help avoid complaints and undesirable water quality. For water utilities in Ohio regulated by the Public Utilities Commission, it is required that the distribution system be flushed at least once per year and all dead ends twice per year. Flushing programs may follow two approaches depending on the issue(s) being addressed: conventional flushing and unidirectional flushing.

### **5.1 Conventional Flushing Program**

A flushing program details the program's objectives, data collection, and flushing process. Utilities might conduct various types of flushing depending on the reasons for flushing. Spot flushing might be conducted in response to specific problems or complaints. Dead-end flushing is often used for dead-end mains with long residence time and a history of complaints. Zone valve flushing might be performed at boundaries of pressure zones where closed isolation valves don't allow circulation of water. System wide flushing is often conducted by an approach called unidirectional flushing. Unidirectional flushing is a particular approach to flushing and is

discussed in Section 5.2. For any program, there are also important program administration issues such as data organization and storage, staffing, infrastructure improvement plans, and public relations. The following outlines the components of a flushing program. No one program would be expected to contain all the elements listed. Section 5.1 summaries material found mainly in the American Water Works Association Research Foundation (AwwaRF) Report titled *Implementation and Optimization of Distribution Flushing Programs* and the AwwaRF Report titled *Development of Distribution System Water Quality Optimization Plans*.

### **5.1.1 Objectives of a Flushing Program**

- To remove accumulated impurities.
- To remove impurities associated with new and repaired mains.
- To remove impurities associated with complaints.
- To remove impurities hazardous to the public health.
- To reduce high bacterial concentrations.
- To reduce chemical contamination.
- To increase chlorine residuals.
- To eliminate tastes and odors.
- To remove discolored water.
- To reduce turbidity.
- To remove accumulated sediment.
- To respond to customer complaints.
- To maintain the life of mains.

### **5.1.2 Basis for a Decision to Flush**

The flushing location might be the entire distribution system for which a unidirectional flushing approach should be considered (see section 5.2, below); portions of the distribution system such as areas with older mains or chronic complaint areas; mains subject to sedimentation; dead ends; and areas of the system identified by water quality monitoring records.

In setting up a flushing program, it must be recognized that flushing may, at least temporarily, make conditions worse. Loosened sediments could cause problems with customer meters and plumbing. High flush velocities might strip protective corrosion control films and lead to corrosion byproducts being released such as red water events in systems with unlined cast iron mains.

### **5.1.3 Data Collection and Monitoring Recommendations**

As part of any flushing program, a utility will operate many valves and hydrants. Special care should be taken to leave the valves in the desired position after flushing. Typically most valves are fully open, and valves at pressure zone boundaries are typically closed. Operation of valves and hydrants during flushing programs may satisfy other utility objectives for valve and hydrant operation, and so record keeping may be important for use in multiple programs. Consideration should be given to collecting the following data related to the flushing program:

- Complaint coded by location, time, date, and type of water quality complaint.

- For each hydrant or blowoff flushed: record date, time, location, pressure zone, size, length of main, static and residual pressure, flushing rate and velocity, time to clear, and total flushing time. These pressure readings and flows, when compared with expected values, can be used to determine if a problem exists nearby.
- Pressures in mains surrounding the flushing area.
- Records of color, clarity, turbidity, dissolved oxygen, pH, and temperature.
- Chlorine residual at the start, middle, and near the end of flushing. The measurement at the start of flushing provides information on water quality and allows for comparison to later measurements. Tests during flushing indicate when water in the segment has been fully replaced. Measurements near the end of flushing verify that full-strength water is present upon completion.
- Visual clarity and “time to clear”. Completion of a flushing event is indicated when both full local chlorine residual and visual clarity are attained. The time required to clear is usually longer than the time to restore full local chlorine residual so the duration of a flushing event is usually equal to “time to clear”. This duration is recorded and the information can contribute to planning future events, understanding system problems, and recognizing trends.
- Lab results for samples collected at the time of flushing.
- Lab results for analyses associated with a monitoring program dedicated to the flushing program.
- Location and time of maintenance work on the distribution system, such as valve replacement or repair, hydrant replacement or repair, main replacement, valve exercising, etc.
- Time and location of fire hydrant testing whether by water utility or fire department.
- Time and location of any unusually high flows such as main breaks or fire fighting.
- Record condition of mains, valves, and fittings removed from the system as indication of corrosion rates.
- Lab results from routine monitoring program of the distribution system for regulatory compliance.

#### **5.1.4 Flushing Process**

The following are background information for system wide flushing:

- Detailed flushing plan for each area based on distribution system maps.
- Flush from source toward periphery.
- Flush one short section of main at a time to maintain distribution system pressure above 20 psi.
- Flushing at night might have less effect on distribution system pressures and capacity and is less apt to produce customer complaints from discolored water.
- Recommend flushing velocities of at least 2.5 fps and up to 10 ft/s is the recommended max per Water Distribution Handbook due to concerns of water hammer during startup and shutdown, depending on the nature of the water quality problem – lower velocities for discolored water, higher velocities for sediment removal.
- Do not try to flush a large diameter main supplied by a single small diameter main.
- Notification of all customers that may be affected by the flushing, particularly customers sensitive to the effects of system flushing, such as hospitals and laundries.

The following outlines the mechanics of field operations:

- Notify affected customers before beginning to flush.
- Isolate sections to be flushed from the rest of the system.
- Close valves slowly to prevent water hammer.
- Open hydrant or blowoff valves slowly until the desired flow is obtained.
- Direct flushing water away from traffic, pedestrians, underground utility vaults, and private lands (diffusers may be required).
- Make sure storm drains or natural water courses can handle the flow.
- Prevent heavily contaminated water from discharging to sensitive water courses.
- Dechlorination may be required.
- Flushing water into a tanker truck may be required.
- Check system pressure around the flushing area for 20 psi minimum. Record flushing data per data collection process.
- When water clears, close hydrant or blowoff valve very slowly to prevent water hammer.
- Reopen valves connecting flushed section to the larger system slowly.
- Proceed to next section to be flushed.

#### ***5.1.5 Program Administration***

The program can be refined or improved with experience. A system should be developed to organize and store data gathered during flushing. Complaint records should be examined to determine which areas of the system need to be flushed and at what time of the year. Routinely flush dead ends and other areas associated with frequent complaints. Analyze time to clear to determine if the period between flushings should be increased or decreased. Experiment with sampling locations and water quality parameters to incorporate water quality testing into the flushing program decisions to flush. Develop costs of labor and equipment, water use, and administration to help assess the benefits of flushing.

Design criteria for extension to the distribution system should be considered. Locate blowoff points at low points to facilitate removal of sediments. Locate hydrants, blowoffs, and valves so the flushing operations will cause minimal disruption to customer service. Design distribution system with enough hydraulic capacity to provide adequate flushing for long periods without lowering system pressure below 20 psi or reducing the system's fire-fighting capacity. Design improvements should eliminate dead-ends where possible. Make allowances for proper disposal of flushing water.

Public relations should be incorporated into the program. Flushing of new, replacement, or repaired mains should follow AWWA Standard C651.

The flushing program should be explained to the public, including the need for flushing in light periods of drought or continuing water conservation programs. Notice should be given to areas that will be affected by flushing and particularly certain categories of customers who are most affected by flushing such as laundries and dialysis patients. Public notice may be made by

portable signs at flushing sites, newspapers, direct mailings, delivered notices, or notices accompanying utility bills.

## 5.2 Unidirectional Flushing

Unidirectional flushing is an effective approach to system wide flushing and for areas of the distribution system that can be properly segregated from the rest of the system. System wide flushing requires rigorous area sequencing and nearly continuous start to finish flushing within a given area.

Proper planning must take place to successfully conduct a unidirectional flushing of a system. Planning will require delineation of discreet main segments and the valves to isolate them. The following summaries material found mainly in an AwwaRF Report titled *Development of Distribution System Water Quality Optimization Plans*.

Important assumptions of the planning are:

- Valves can be closed only if service is maintained to all customers.
- A minimum pressure of 20 psi must be maintained everywhere in the system at all times.
- The point of beginning of each segment will be on a main at or near a branch or intersection that leads to a hydrant. The end point will always be a hydrant or blow-off.
- Isolated subsystems (those without a second source of water) should be flushed first. If this can not be done, caution should be exercised for subsystems that are up gradient to avoid sediment contributions to the flushed area.
- It might not be possible to implement complete unidirectional flushing for isolated subsystems with limited or no loops. To do so might isolate a dead-end side street with no other source of water.

Here is a planning outline for unidirectional flushing:

- Identify a target area with the following characteristics:
  - Completely within one pressure zone.
  - At least one source of clean water for the point of beginning.
  - Reasonably well protected from inflow by routine flow vectors.
  - Delineated in a way that does not isolate adjacent mains.
  - Coordinated (delineated and sequenced) with other target areas and the system and sources overall.
  - Have routine flow directions that allow for a source-to-perimeter sequence of clean water flow that generally follows the routine flow directions.
- Gather data:
  - Identify all clean water sources at perimeter of, or within, target area.
  - Compile information on pipe sizes, valves, hydrants, and directions of routine flow.
  - Generally consider which water sources will be used to flush which parts of the target area and select one to start.

- Identify critical customers (high demands and sensitive users such as hospitals).
- Compile maps and other information for consideration of receiving water of conveyance and for traffic and safety.
- A program of unidirectional flushing is laid out by starting at the furthest down-stream point of known clean water and flushed pipe and defining the first pipe to be flushed by the following criteria:
  - Immediately downstream of the beginning point.
  - Extend as far as possible but not more than 1,000 feet (typical).
  - Can be isolated from any 2<sup>nd</sup> source of water.
  - Does not have routine flow velocities greater than 4 fps (if greater than 4 fps then flushing may not be necessary).
  - Does not extend past any of the following:
    - A change in pipe size.
    - A large branch, which cannot be temporarily eliminated by closing a valve because there is no valve installed on the branch or because closing it would disconnect customers. The utility should consider closing the nearest valve first on original main and including “branch” as continuation of first segment.
    - An intersection where source water from un-flushed segments will flow into the subject when the valves closed for the purpose of isolating the subject segment are re-opened (i.e. don’t go too far and include footage that may be re-contaminated and have to be flushed again during a later segment). Additionally, the utility should minimize double flushing.
- Delineate and sequence additional segments by the criteria above and the following:
  - Address “one-segment” branches off segment previously flushed. These may be lines leading into adjacent target areas or dead-ends that were temporarily ignored. Consider such segments as candidates for next in sequence, but flushing may not be delayed for some, depending on circumstances.
  - Examine all loops within the subject target area that include the previously flushed segment(s) and select which loop will be flushed (completely) next. Employ the following criteria as applicable:
    - Complete loops close to area starting point before beginning loops further from it.
    - Sequence loops to minimize length of “clean perimeter” and simplify valve operations.
    - Avoid overlap into segments better flushed from another clean source, if any.
- Determine sequence of segments (including next segment) around selected loop on the following criteria:
  - Simplify valve operation and tracking.
  - Minimize travel.
  - Establish last flush near far end of loop (i.e. come around from both sides).

- Consider segments with routine flow velocities greater than 4 fps for possible exclusion from flushing. Exclude if doing so does not interrupt process or potentially deliver not-yet-“clean” water as source water to future segments.

This process should be repeated until the entire area to be flushed with a given source water is complete, and then go to another area to begin the process again.

### **5.3 Applicable Guidance for Flushing Programs**

AwwaRF, *Implementation and Optimization of Distribution Flushing Programs*, 1992  
AwwaRF, *Deterioration of Water Quality in Distribution Systems*, 1987.  
AwwaRF, *Development of Distribution System Water Quality Optimization Plans*, 2005  
ANSI/AWWA Standard C651, “Disinfecting Water Mains”.

## **6.0 HYDRAULIC CONSIDERATIONS**

As previously mentioned, the focus of this white paper is optimization of distribution systems for water quality improvements. Thus, it is not the intent to provide a lot of detail regarding hydraulic constraints or problems and strategies to eliminate them. That being said, system hydraulics can impact distribution water quality. Some of the most common hydraulic problems impacting water quality are hydraulic surges and areas of low or negative pressure resulting from changes in flow direction (flow reversal) and high and low flow conditions. Use of high-speed pressure monitoring can help to identify pressure transients (duration and magnitude). A maximum pressure variation of 20 psi is recommended.

### **6.1 Hydraulic Surges**

Hydraulic surges, frequently referred to as “water hammer”, are caused by abrupt changes in velocity and can cause line breaks resulting in intrusion of microbiological contaminants (e.g., bacteria) naturally present in the surrounding soil. In addition to line breaks, hydraulic surges can disrupt existing pipe scales, disturb biofilms, and suspend accumulated sediments in distribution piping. Such events can lead to taste and odor, color, or other customer complaints and reduce consumer confidence. Soft-starts on distribution pumps, controlled-closing of distribution valves, air-release valves, pressure-reducing valves, and other systems controls can help to eliminate hydraulic surges.

### **6.2 Areas of Low or Negative Pressure**

In addition to water hammer, areas of the system with extremely low or negative pressure, may also experience water quality degradation. Negative pressures, like water hammer, are caused by abrupt changes in velocity. For example, consider a valve in the distribution system. If that valve is closed instantaneously, the water will decelerate to zero velocity and the kinetic energy will be converted to pressure. Since the valve in this case is closed, there is nowhere for that pressure to go but backward, creating a negative pressure water. This negative pressure situation has the potential to backsiphon, or suck, non-potable water from domestic (household), industrial, or other plumbing back into the distribution system. Further, the negative pressure allows for the

intrusion of microbial contaminants (i.e., bacteria) in the surrounding soils to intrude through leaking or corroded pipes. It is for this reason, that Ohio EPA recommends a minimum system pressure of 20 psi at all locations in the distribution system. As with water hammer, soft-starts on distribution pumps, controlled-closing of distribution valves, air-release valves, pressure-reducing valves, and other systems controls can help to eliminate negative pressure in the distribution system.

### 6.3 Additional Reading

AwwaRF, *Guidance for Management of Distribution Systems Operation and Maintenance*  
AWWA G200, *Distribution Systems Operation and Management*  
Ohio EPA Backflow Prevention and Control Manual Third Edition 2013,  
[http://epa.ohio.gov/portals/28/documents/rules/draft/OEPA\\_BPCC\\_RevisionsManual\\_2013.pdf](http://epa.ohio.gov/portals/28/documents/rules/draft/OEPA_BPCC_RevisionsManual_2013.pdf)

## 7.0 HYDRAULIC AND WATER QUALITY MODELING

Water distribution system models offer an effective way to determine water age, flow patterns, system pressures, and, in some cases, water quality (e.g., disinfectant residual). Development of a distribution model, however, is a complex effort often requiring significant resources. In utilities with limited manpower, and in smaller utilities in particular, this may require hiring of new staff or an engineering consultant.

To predict water age accurately, the model should include the majority of the pipes in the distribution system and all physical facilities (such as storage tanks, pumps, and valves), provide an accurate simulation of water demand, and be well-calibrated. Such a model can be used to quickly and accurately simulate complex water systems under various operating conditions. The hydraulic models can be used to determine the need for and the effect of various methods to reduce hydraulic residence time such as looping dead-ends, blow-offs, closing/opening valves, and replacing large diameter pipes with smaller ones. There are some hydraulic models available that have these capabilities, and one such model that is available in the public domain is called **EPANET**. This hydraulic model is available for free from USEPA and can be downloaded from the following internet address:

<http://www.epa.gov/nrmrl/wswrd/dw/epanet.html>

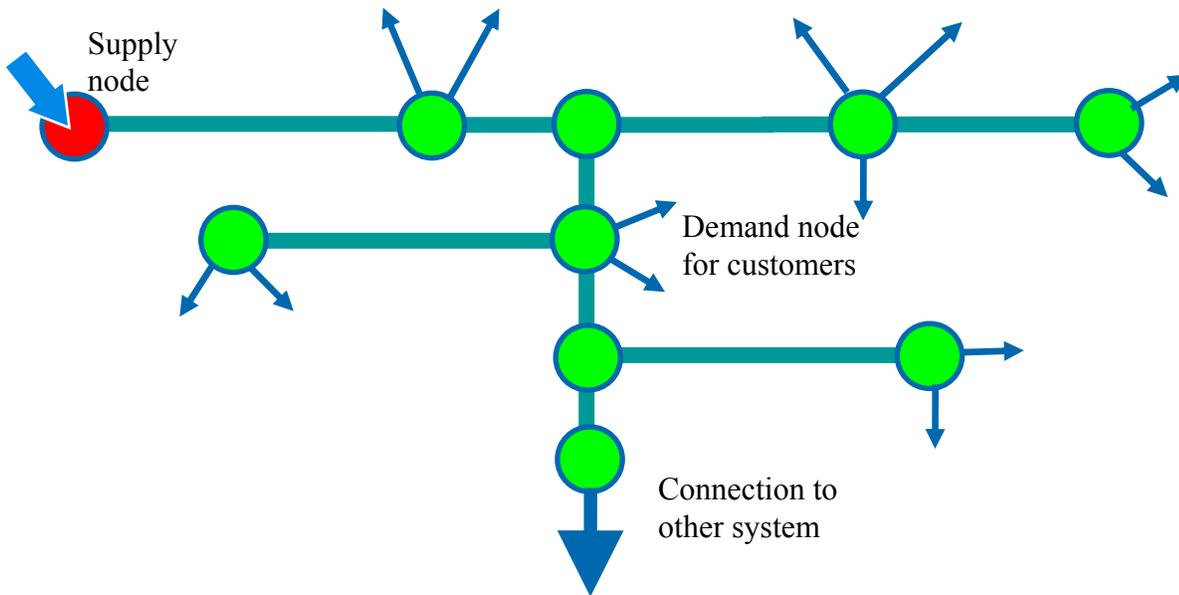
Water distribution systems consist of buried transmission mains and distribution piping. The distribution system is designed to deliver water to customers, and less than 1 percent is monitored regularly for both water quantity and quality. It is typical to measure hydraulic parameters like flow and pressure at pumping stations, and water quality parameters like disinfectant residual at tanks and reservoirs in the distribution system. However, almost no effort, other than required regulatory monitoring, is made to monitor these parameters in the remainder of pipes in the field.

### 7.1 Modeling Basics

Water distribution system models consist of two elements: nodes and links. Nodes are used to connect pipes, to represent where water leaves a system (demand allocation), and/or to identify water supply and storage. Links are pipes, valves and pumps. The red node in Figure 7 is a

supply node where water enters the system and represents a treatment plant, a well or a connection to another system. The green nodes may represent places for demand allocation, and can represent single users or groups of users, or connections to other systems in the model.

**Figure 7. Water Distribution System Model Consisting of Nodes and Links**



After a distribution network is built with treatment plants, pumping stations, storages, water mains and customer demands, roughness coefficient is assigned to mains globally based on pipe material and age, and system controls are entered for pumps and valves to mimic actual operation. Following this global step, the model goes through calibration to improve results such as pressure, level and flow by adjusting globally assigned pipe roughness based on local condition. Also, the model needs to be updated annually to reflect changes in the distribution system such as new and abandoned infrastructure and demand variation from retail/wholesale customers. After updates, a validation of the model is recommended to confirm accuracy of modeling results.

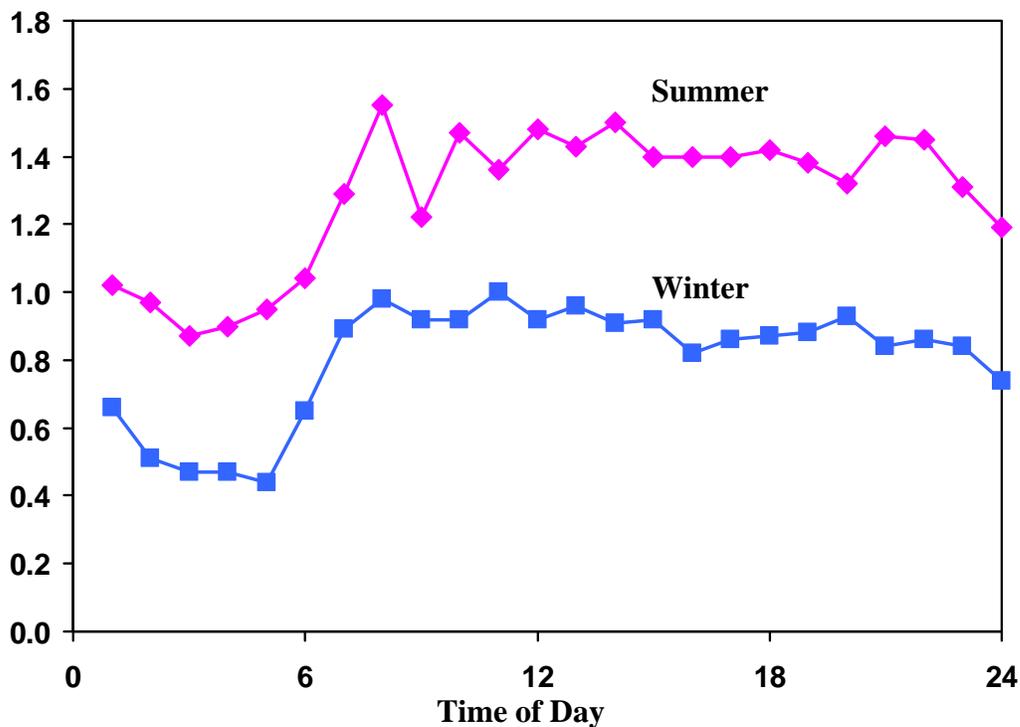
There are various ways to define characteristics of a water distribution system model. Based on a model's detail, it is defined as either a "skeletonized" or "all pipe" model. Based on operation scenarios, it is defined as either a "steady-state" or "extended period simulation" model. Based on a model's functions, it is defined as either a "hydraulic" or "water quality" model. Each of these terms are defined below.

*Skeletonized vs. all pipe models.* When water distribution system models were first introduced in the 1960s, they could include a limited number of pipes due to restrictions in speed and memory of computers. Back then, a distribution system was skeletonized to include hydraulically significant pipes in a computer model, excluding less significant pipes. Skeletonized models tend to have all transmission mains (pipe ID  $\geq 16''$ ), most of dual service mains ( $16'' > \text{pipe ID} \geq 10''$ ), and some of distribution mains (pipe ID  $< 10''$ ). The skeletonized models used to be popular for hydraulic analysis like master planning and fire flow testing. With increased interest on water

quality in the 1990s, distribution system models started incorporating pipes with such problems which were often distribution mains near the end of the system or division valves. In contrast, all pipe models include every pipe of the distribution system in the model. Recent advancement in computer technologies made it feasible to build such models. However, water quality predictions at pipes with low flow still need further development to improve accuracy.

*Steady-state vs. extended period simulation.* Early water distribution system models were set up to simulate only steady-state hydraulics where system demand and operation do not vary with time. Steady-state models were used to determine if a pipe network could deliver water with adequate flow and pressure at various system conditions including maximum day and peak hour demands. In reality, hourly fluctuation of demands from customers drives operation of the distribution system, and extended period simulation (EPS) models were introduced to account for changes in demand over the course of a day in the 1970s. EPS models are essential to perform any tasks related to water quality in the distribution system, and require both demand amount and patterns describing how the water is taken out of each node over a certain period of time, typically 24 hours as Figure 8 shows.

**Figure 8 Example Water Demand Pattern**



*Hydraulic vs. water quality.* With the introduction of the free EPANET model in the 1990s, water distribution system models now allow for two types of prediction: hydraulic and water quality. When a model begins to simulate a target water distribution system, the hydraulic module first analyzes pressure and elevation for nodes, and pressure and velocity for links. Based on outputs from hydraulic simulation, a water quality module can then be used to simulate the source of water (e.g., which treatment plant or well), water age, chlorine concentration, DBP

concentrations, and contaminant transport for both nodes and links. Without a good hydraulic model, an accurate water quality model can not exist.

## 7.2 Model Applications

Distribution system models for hydraulics and water quality have many uses in water utilities. The most common applications are described below. Table 7.1 lists various applications and the type of model that is appropriate for each application.

*Master planning.* Planners can use network models to determine if capital improvements are required to meet current and future demand through rehabilitation of the existing system and/or expansion, and to prioritize needed improvements. Recent trend for master planning tends to consider both water quantity and quality in these analyses.

*Regulations.* Disinfectant residual and DBP concentrations can be predicted using the water quality module of the model to find potential areas with low disinfectant or high DBP concentrations before actual problems develop. Various changes can be made to disinfectant dose, tank turn-over, pumping schedule and valve status in the model to find effective solutions to real problems. As noted above, however, prediction of non-conservative parameters requires extensive model calibration and validation.

*Security.* To protect a distribution system from both intentional and unintentional contamination, a water quality module can be used to select locations for online monitors to detect contamination for warning as soon as possible. When contaminants are found in a distribution system, water quality modules can trace transport of the contaminants to isolate affected areas and notify the affected customers, to locate the contamination source, to identify locations for confirmatory sampling, and to develop decontamination strategies including flushing.

*Customer complaints.* Network models can be used to develop flushing plans for a distribution system. When customer complaints are reported, a water quality module can be used to identify its potential source in the system and to plan effective remedial action.

*System operation.* Operators can use network models to understand how operation of pumps, valves and tanks affects system hydraulics. This helps to determine range to maintain proper flow, pressure and level for daily operation, and to train new operators.

*Other.* Hydraulic module of the network model helps to determine if a distribution system can meet fire protection requirements for flow and pressure. If the requirements are not met, the module can be used to correct the situation. The module also helps to save energy costs by determining energy usage of pumps according to various operation scenarios.

**Table 3. Water Distribution System Model Types and Recommended Applications**

Model Applications	Types of Water Distribution System Model							
	Skeletonized	All Pipe	Steady-State	EPS	Hydraulic	Water Quality		
						Source of Water	Water Age	Chemical Transport
<b>Master Planning</b> - CIP - rehabilitation - system expansion	√ √ √		√ √ √	√√ √√ √√	√ √ √	√√ √√ √√	√√ √√ √√	√√ √√ √√
<b>Regulation</b> - free chlorine residual - THMs/IDSE	√ √	√√ √√		√ √			√	√ √√
<b>Security</b> - sensor location selection - contaminant tracing - contaminant containment	√ √ √	√√ √√ √√		√ √ √			√	√* √*
<b>Customer Complaints</b> - flushing plan - source of colored water - colored water prevention	√ √ √	√√ √√ √√		√ √ √	√	√	√√ √	
<b>System Operation</b> - daily operation - operator training	√ √			√ √	√ √		√√ √√	
<b>Other</b> - energy management - fire flow analysis	√ √		√ √	√√ √√	√ √		√√	

Note: √ Marked model types are required for the application.  
 √√ Marked model types can enhance the application.  
 √\* The applications need information from EPA's Water Contaminant Information Tool.

### **7.3 Additional Reading**

AWWA M32 Computer Modeling of Water Distribution Systems

WRF 4018 Guidelines for Developing, Calibrating, and Using Hydraulic Models

EPA/600/R-06/028 Water Distribution System Analysis: Field Studies, Modeling and Management-A Reference Guide for Utilities 2005

## **8.0 CONCLUSIONS AND RECOMMENDATIONS**

Recent research has demonstrated the impact, often significant, of the distribution system on water quality. Similarly, the number of regulations focusing on maintaining distribution water quality is continuing to increase. For these reasons, it is important that drinking water utilities evaluate the impacts of their distribution system on the water quality they provide to their customers and, when possible, make physical or operational improvements to minimize water quality degradation in the distribution system. This white paper discusses the distribution system factors that can impact water quality and provides guidance to evaluating those impacts and identifying changes to minimize those impacts. Utilities are encouraged to take steps to minimize water quality degradation in the distribution system.