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Distribution System Issue Paper

Effects of Water Age on Distribution System Water Quality

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Background and Disclaimer

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objectives of the issue papers are to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant identify areas in which additional research may be warranted. The issue papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

Additional Information

The paper is available at the TCR web site at:

http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html

Questions or comments regarding this paper may be directed to **TCR@epa.gov.**

Effects of Water Age on Distribution System Water Quality

1.0 Introduction

Water age is a major factor in water quality deterioration within the distribution system. The two main mechanisms for water quality deterioration are interactions between the pipe wall and the water, and reactions within the bulk water itself. As the bulk water travels through the distribution system, it undergoes various chemical, physical and aesthetic transformations, impacting water quality. Depending on the water flow rate, finished water quality, pipe materials and deposited materials (i.e., sand, iron, manganese), these transformations will proceed to a greater or lesser extent. The goal of this document is to review existing literature, research and information on the potential public health implications associated with the decay of water quality in distribution systems piping networks with time.

2.0 General Description of Topic

2.1 Factors Contributing to Increased Water Age

In addition to meeting current demands, many water systems are designed to maintain pressures and quantities needed to meet future demands or to provide extra reserves for fire fighting, power outages and other emergencies. The impacts of these design practices on water age are discussed below.

2.1.1 Demand Planning

Capital planning necessitates installation of facilities that have excess capacity for water storage and distribution. It is normal practice to size pipelines for water demands that will occur 20 years or more into the future. Building distribution facilities that are large enough to accommodate future demand can in the near term increase water age as the storage volume in the constructed facility may be large relative to the present day demand. Changes in water demands or use patterns, such as those caused by the relocation of an industrial water user, annexation of a neighboring system, or consolidation of multiple systems, can have a significant impact on water age.

Water demand variations also occur on a daily basis. Daily demand variations can be shown on a diurnal demand curve, which plots the percentage of daily demand versus time. Figure 1 shows a diurnal curve for a utility that serves approximately 100,000 people, and illustrates how maximum water use varies over a 24-hour period, based on maximum day demand (MDD) conditions. The figure also shows that the peaking factor for residential users is slightly larger than the commercial factor, and that peak demands occur at different times of the day for the two user groups. Review of the composite usage pattern suggests that typically, water age due to storage in the distribution system is highest in the early morning hours and lowest in the late evening (see Figure 2).

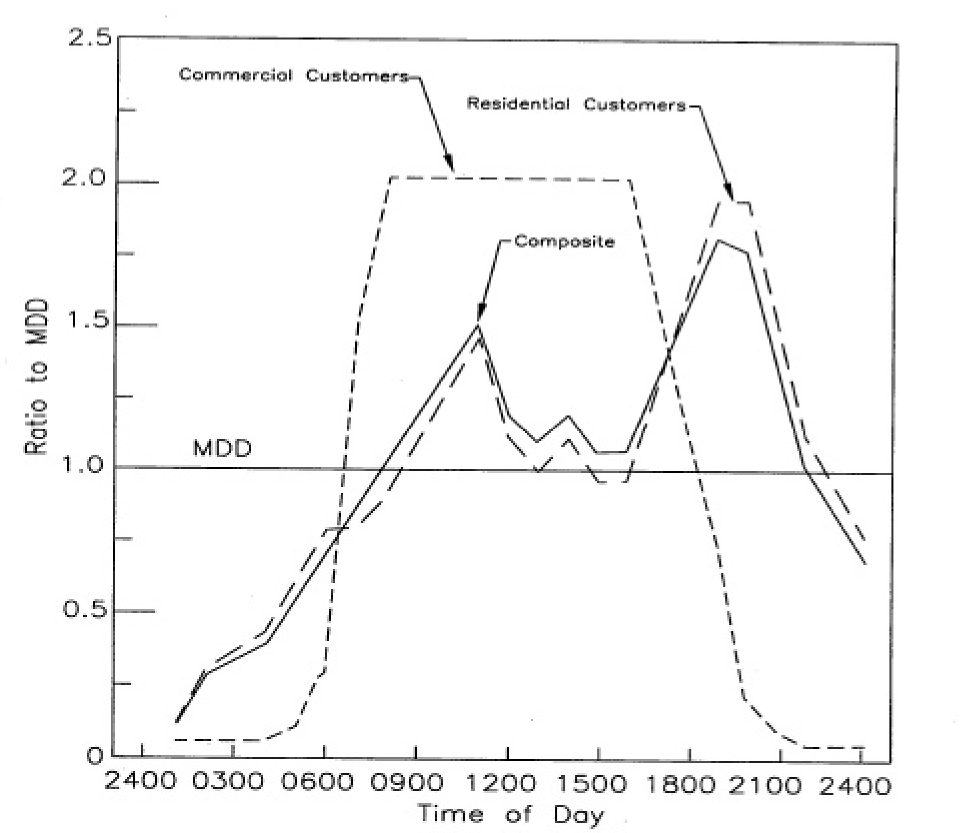

Figure 1
Diurnal Curve Peaking Data

Figure 2 shows the standard diurnal demand curve developed by AWWA based on average day flows (AWWA Manual M32, 1989).

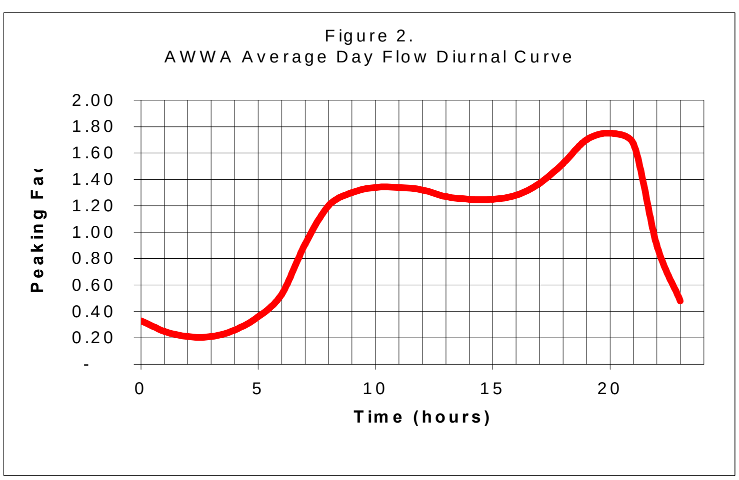

Figure 2
AWWA Average Day Flow Diurnal Curve
(Source: AWWA Manual M32)

2.1.2 Fire Flow Requirements

The effect of fire flow requirements on drinking water reservoir and distributions system capacity must be quantified on a system-specific basis. The American Water Works Association Manual M31 *Distribution System Requirements for Fire Protection* (1998) states the following:

> "The decision of whether or not to size distribution system components, including water lines, appurtenances, and storage facilities for fire protection must be made by the governing body of the community. This decision is made in conjunction with the water utility if the utility is privately owned. ..."

Most States require consideration of needed fire flow and may direct the designer to a local fire official and a particular technical method. Three such methods are presented in AWWA Manual M31 including:

- Insurance Services Office Method,
- Iowa State University Method, and
- Illinois Institute of Technology Research Institute Method.

The Fire Suppression Rating Schedule is the manual the Insurance Services Office (ISO) uses in reviewing the fire-fighting capabilities of individual communities. Forty percent of the grading ISO gives is based on the community's water supply. This part of the ISO survey focuses on whether the community has sufficient water supply for fire suppression beyond daily maximum consumption. ISO surveys all components of the water supply system, including pumps, storage, and filtration. (ISO, 2000). Fire flow requirements for buildings are also given in the Uniform Fire Code (1997) but the specific technical method is not identified. Each method analyzes a specific building and is not based on system-wide considerations. According to AWWA Manual M31, comparisons between the various techniques for computing fire flow are not easily made, because each situation to which the fire flow calculation is applied varies greatly.

While each method may produce different design flow rates for a given building, once a flow rate is calculated, an appropriate duration of time over which that flow rate should be applied must be determined. In Table 1, fire flow rates and durations provided by the Uniform Fire Code (1997) were used to calculate a fire flow volume.

Table 1
Fire Flow Rates, Durations and Volumes.[1]

Fire Flow Rate (GPM; at a minimum pressure of 20 psi.)	Fire Flow Duration (Hours)	Calculated Volume (Gallons)[2]
Up to 2875	2	345,000
From 2875 to 3875	3	697,000
Above 3875	4	1,920,000

1. Adapted from the Uniform Fire Code (1997)
2. Calculated Volume = Maximum fire flow rate multiplied by duration.

It is important to note that only a portion of the calculated fire flow volume is provided by storage created specifically for fire flow. The Water Distribution System Handbook (Mays,

2000) provides the following equation (Equation 1) which is based on the Fire Suppression Rating Schedule (Insurances Services Office, 1980), and other information regarding what portion of the fire flow rate must be provided from storage (all quantities are in flow units, i.e., volume per time):

$$SSR = NFF + MDC - PC - ES - SS - FDS \qquad \text{(Eq. 1)}$$

Where:
SSR = Storage Supply Required,
NFF = Needed Fire Flow,
MDC = Maximum Daily Consumption,
PC = Production Capacity, which is based on the capacity of (the) treatment plant, the well capacity or the pump capacity, depending on the system
ES = Emergency Supply, or the water that can be brought into the system from connections with other systems
SS = Suction Supply, or the supply that can be taken from nearby lakes and canals during the fire, and
FDS = Fire Department Supply, or water that can be brought to the fire by trucks.

Equation 1 shows that fire flows should be achievable in addition to and simultaneous with, flows associated with maximum daily consumption. It also shows that several supply variables can affect the need for storage related to fire flow. Figure 3 is an example of the reservoir storage components required by the Washington State Department of Health Water System Design Manual (1999). The figure illustrates the relatively minor portion of "operational storage" compared to the "equalizing" and "emergency" components.

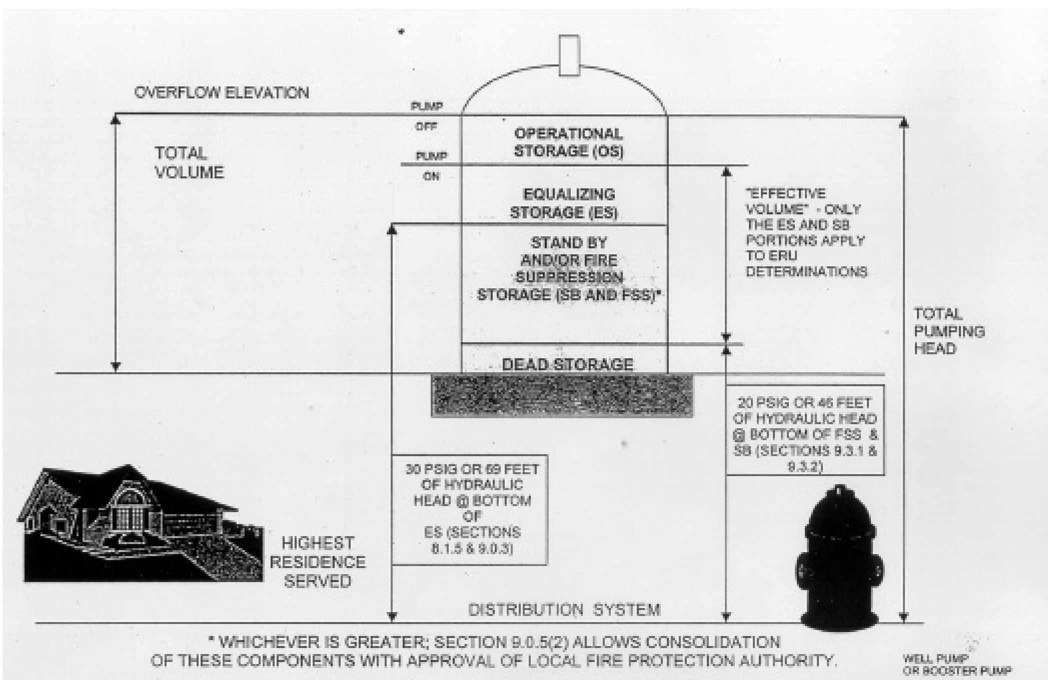

Figure 3
Reservoir Storage Components

According to AWWA Manual M31, one of the most significant distribution system impacts from fire flow requirements includes providing adequate storage capacity and meeting requirements for minimum pipe sizes (e.g., 6-in. [150-mm] pipes in loops and 8-in [200-mm] dead ends) in neighborhood distribution mains when much smaller pipes would suffice for delivery of potable water only. Recommended Standards for Water Works (Ten State Standards, 1997) specify a minimum pipe size of six inches at all locations for providing fire protection. Table 2 shows the volumetric effect of increased pipe diameter on a per-mile basis.

Table 2
Pipe diameter vs. Pipe Volume (per mile)

	Pipe Diameter						
	2”	4”	6”	8”	10”	12”	18”
Gallons per mile	862	3,466	7,755	13,786	21,540	31,019	69,792

Thus, for every mile of 4-inch pipe that is replaced with 8-inch pipe, the effective volume of the distribution system increases by greater than 10,000 gallons.

In summary, the effects of fire-flow considerations on system volume and water age vary greatly from system to system. Few generalizations can be drawn, but AWWA Manual M31 does offer this:

> “In larger systems fire protection has a marginal effect on sizing decisions, but in smaller systems these requirements can correspond to a significant increase in the size of many components. In general, the impact of providing water for fire protection ranges from being minimal in large components of major urban systems to being very significant in smaller distribution system pipes and smaller distribution systems.”

AWWA Manual M31 also states that most communities are willing to incur the higher cost for sizing distribution systems for fire flow requirements because of the reduction in property loss that is possible by using the water system for fire protection. Local planning and zoning ordinances require specific fire flows for various developments (i.e., single family, multiple-family, commercial, industrial, etc.), thus mandating the upsizing of installed distribution system piping. The AwwaRF study *“Impacts of Fire Flow on Distribution System Water Quality, Design, and Operation”* (Snyder et al., In Press) is scheduled for publication in 2002.

2.2 Determination of Water Age

The Water Industry Database (AWWA and AwwaRF 1992) indicates an average distribution system retention time of 1.3 days and a maximum retention time of 3.0 days based on a survey of more than 800 U.S. utilities. The literature cites examples of both “short” (i.e., less than 3 days) and “long” (i.e., greater than 3 days) water ages. Several water age estimations published in the literature are summarized in Table 3 and are described below.

Table 3 Summary of water age evaluations			
Population Served	**Miles of Water Mains**	**Range of Water Ages within System (Days)**	**Method of Determination**
750,000*	1,100	<1 – 3	Fluoride Tracer
800,000	2,750	3 – 7+	Hydraulic Model
87,900*	358	> 16	Chloramine Conversion
24,000	86	12 – 24	Hydraulic Model

*Estimated by using 2.5 multiplier on number of customers served.

As discussed previously, water age is a function primarily of water demand, system operation, and system design. As water demand increases, the amount of time any given liter of water is resident in the distribution system decreases. Demand is related to land use patterns, types of commercial-industrial activity present in a community, the weather (i.e., lawn watering), and water use habits of the community (i.e., conservation practices, reuse practices). Conservation, particularly use of reclaimed water on-site or through separate distribution systems, will tend to lead toward greater water age when all other factors are held constant. The following four examples illustrate how water age varies from community-to-community as a result of these factors.

- A utility in North Carolina serving 300,000 customers with 1,100 miles of main calculated water ages ranging from 2 to 75 hours throughout the distribution system using a fluoride tracer study (DiGiano, Travaglia and Zhang 2000).

- A Midwest utility with a service population of 800,000 and 2,750 miles of main recently found based on a hydraulic model that the water age in the distribution system was typically less than 80 hours while several sites exhibited a water age up to 150 hours (Vandermeyden and Hartman 2001).

- One California utility found water ages exceeding 400 hours in certain areas of the system, particularly dead end areas, under minimum day and average day demand conditions (Acker and Kraska 2001).

- A Canadian utility serving 24,000 people with 86 miles of main estimated water age using a hydraulic model and found that dead-end nodes had a water age ranging from 300 to 600 hours under average day demand conditions (Prentice 2001).

Consequently the importance of water age as a significant driver for water quality conditions in these distribution systems is variable from system-to-system and even within each system.

The objective of a new AwwaRF Study (#2769) entitled "Evaluating Retention Time to Manage Distribution System Water Quality" is to evaluate the feasibility and effectiveness of using distribution system retention time (or water age) as a tool for managing distribution system water quality. This study will provide case and field study examples of actual system detention times, and will document impacts of water age on distribution system water quality.

2.3 Water Quality Problems Associated With Increased Water Age

Table 4 lists water quality problems that can be caused or worsened by increased detention time in the distribution system. Those items marked with an asterisk were identified as having direct potential health impacts, and are discussed further in this White Paper or in other White Papers. Other items may impact water quality, but direct health impacts have not been identified.

Table 4
Summary of water quality problems associated with water age

Chemical issues	Biological issues	Physical issues
*Disinfection by-product Formation	*Disinfection by-product Biodegradation	Temperature increases
Disinfectant decay	*Nitrification	Sediment Deposition
*Corrosion control effectiveness	*Microbial regrowth / recovery / shielding	Color
Taste and odor	Taste and odor	

* Denotes water quality problem with direct potential public health impact.

3.0 Potential Health Impacts

Various potential health impacts have been associated with the chemical and biological issues identified in Table 4. The Chemical Health Effects Tables (U.S. Environmental Protection Agency, 2002a) provides a summary of potential adverse health effects from high/long-term exposure to hazardous chemicals in drinking water. The Microbial Health Effects Tables (U.S. Environmental Protection Agency, 2002b) provides a summary of potential health effects from exposure to waterborne pathogens.

3.1 Disinfection By-Product Formation

Disinfectants can react with naturally occurring materials in drinking water to form organic and inorganic disinfection by-products (DBPs). With over 200 million people served by public water systems that apply a disinfectant, there is a very large population potentially exposed to DBPs through drinking water in the U.S. (USEPA 1998).

The DBP formation potential for each system's water is a function of several chemical and physical characteristics including type and level of organic matter, type and level of specific inorganic parameters, pH, temperature, type and level of disinfectant residual, and contact time. As water ages, there is a greater potential for DBP formation. Higher water temperatures during summer seasons can increase DBPs as the chemical reactions proceed faster and go further at higher temperatures. Also, higher water temperatures often cause a higher chlorine demand, requiring an increased disinfectant dose and resulting in higher DBP formation potential. Decreases in HAA5 concentrations in some distribution systems are attributed to microbial activity.

The USEPA has identified the following potential adverse health effects associated with HAA5 and TTHMs:

> "Some people who drink water containing haloacetic acids in excess of the MCL over many years may have an increased risk of getting cancer. Some people who drink water containing trihalomethanes in excess of the MCL over many years may experience problems with their liver, kidneys, or central nervous system, and may have an increased risk of getting cancer."

The forthcoming Stage 2 Disinfectants and Disinfection Byproducts Rule will change existing National Primary Drinking Water Regulations which consist of maximum contaminant levels and monitoring, and reporting requirements for total trihalomethanes, and haloacetic acids. EPA believes the implementation of the proposed Stage 2 Disinfectants and Disinfection Byproducts Rule will reduce peak and average levels of disinfection byproducts in drinking water supplies which will result in a further reduction in risk from cancer.

The forthcoming Stage 2 Disinfectants and Disinfection By-Products Rule is expected to include a new monitoring and reporting approach. Compliance with TTHMs and HAA5 standards will be based on a locational running annual average using monitoring data gathered at new monitoring locations selected to capture representative high levels of occurrence. MCL violations could potentially occur at single locations such as a finished water storage facility due to site-specific situations, including excessive water age or chlorine addition at the storage facility.

3.1.2 Biodegradation of Disinfection Byproducts

Biodegradation of some HAA species has been observed over several years in a southeastern U.S. utility and at other utilities (Williams, Williams and Gordon 1996). An evaluation of the water quality in the southeastern U.S. utility did not reveal any unusual conditions other than relatively low residual chlorine levels and a high heterotrophic bacteria count (Williams, Williams and Gordon 1996). A certain bacillus species (*X. autotrophicus*) is reported to be capable of degrading dichloroacetic acid and dibromoacetic acid, but not trichloroacetic acid (Williams, Rindfleisch and Williams 1994; Baribeau et al. 2000).

The proposed Stage 2 DBPR monitoring strategy requiring systems to identify representative high TTHMs and HAA_5 formation locations (not necessarily maximum residence times) will address this issue. According to the July 27-28, 2001 Federal Advisory Committee (FACA) meeting summary, Initial Distribution System Evaluation (IDSE) studies can be based on various data sources including historical TTHM and HAA_5 data, calibrated network hydraulic models, and tracer studies, in place of, or in combination with, an intensive monitoring program. Associated guidance is anticipated to identify biodegradation of HAAs as an issue to consider in selecting Stage 2 DBPR monitoring locations.

3.2 Nitrification and Microbial Regrowth

Nitrification is a microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate. Nitrifying bacteria are slow growing organisms, and nitrification problems usually occur in large reservoirs or low-flow sections of the distribution system. According to Kirmeyer et al (1995), operational practices that ensure short residence time and circulation within the distribution system can minimize nitrification problems. Low circulation areas of the distribution system are the types of locations where nitrification is more likely to occur since detention time and sediment buildup can be much greater than in other parts of the system.

Under the Safe Drinking Water Act (SDWA), primary MCLs have been established for nitrite-N, nitrate-N, and the sum of nitrite-N plus nitrate-N. The MCLs are 1 mg/L for nitrite-N, 10 mg/L for nitrate-N, and 10 mg/L for nitrite + nitrate (as N). The nitrite and nitrate MCLs are applicable at the point-of-entry to the distribution system. Review of nitrification episodes and information gathered from the literature indicates that an MCL exceedence within the distribution system due to nitrification is unlikely, unless source water nitrate-N or nitrite-N levels are close to their applicable MCLs. Additional information related to nitrate and nitrite formation is provided in the Nitrification White Paper.

Much research has been conducted related to the growth of microorganisms within the distribution system. There are numerous factors that impact microbial growth rate, many of which are related to increased water age. These include temperature, system hydraulics, nutrient availability, and disinfectant efficacy, among others. A detailed discussion of health implications associated with the survival and/or growth of pathogens within the distribution system is provided in a separate White Paper.

3.3 Corrosion Control Effectiveness

Corrosion control effectiveness can be related to water age. With increased detention time there are impacts on the effectiveness of phosphate inhibitors and pH management in poorly-buffered waters.

The use of orthophosphates has been a successful practice for minimizing corrosion of piping and materials containing lead and copper. For utilities with hard water and high levels of dissolved inorganic carbonate (DIC), blended ortho- and poly-phosphates have been used. Many polyphosphates, particularly those of the linear chain variety, tend to hydrolyze, i.e., convert to orthophosphate to some degree with time and passage through the distribution system. (Economic and Engineering Services, Inc; Illinois State Water Survey; 1990). Reversion to orthophosphate can limit the effectiveness of blended ortho- and poly-phosphates as corrosion control inhibitors.

pH stability can be difficult to achieve for utilities with soft, poorly-buffered waters, especially in portions of the system with increased water age. Interaction with cement linings can significantly increase pH (as discussed in the Permeation and Leaching White Paper), and unstable, soft, low-mineralized waters can revert to untreated water pH conditions by the time the water reaches the customer's tap. These waters are common in surface water supplies of the Pacific slope, New England, and the southeastern United States (Economic and Engineering Services, Inc,; Illinois State Water Survey; 1990).

Requirements for installing and maintaining effective corrosion control treatment are addressed under the USEPA Lead and Copper Rule. Utilities are required to maintain optimal water quality parameters at the point of entry to the distribution system and at several locations within the distribution system. Problems associated with increased water age and corrosion control effectiveness may impact compliance with water quality parameter requirements or with lead and copper action level compliance.

4.0 Prevention/Mitigation Methods

4.1 Tools for Determining Water Age

Tracer Studies

Tracer studies have been performed to calculate water age throughout a distribution system, calibrate water quality and hydraulic models, and to enhance the study of water age in relation to water quality parameters such as chlorine residual or trihalomethanes. Tracer studies can utilize injected chemicals such as fluoride, or calcium chloride. Alternatively, in systems with multiple sources with varying water quality characteristics (such as differences in water hardness or conductivity); these natural constituents can be used as the tracer. Finally, during transitional periods in system operation, such as changeovers from chlorination to chloramination, the resulting constituents can be traced. Other utilities have taken advantage of a fluoride system shut down, use of alternative water sources, or a switch in coagulant to trace water through the distribution system.

Consideration of the tracer chemical stability, continued regulatory compliance, and customer perceptions must be included in the planning and implementation of a tracer study. For example, if fluoride is used as a tracer, it may be preferential to discontinue fluoride feed so that interference with fluoride uptake on pipe walls for newly-fluoridated systems can be avoided. Conversely, State health departments may not allow for the purposeful discontinuation of fluoridation. Although lithium chloride is used as a tracer in the United Kingdom, customer acceptance in the United States has prevented its wide-spread use. Table 5 (Smith, Grayman, and Friedman, N. P.) provides a summary of example tracers and associated research and development needs.

Table 5
Example Tracer Summary Matrix

Tracer	Research and Development Needs	Regulatory Issues	Problems/Comments
Fluoride	Continuous on-line monitor for use in distribution system	Difficulties in adding or shutting off fluoride in some places	May be non-conservative due to pipe wall uptake in systems that do not normally use fluoride.
Sodium chloride	NA	NA	Requires relatively large volumes of tracer
Calcium chloride	NA	NA	NA
Lithium chloride	NA	NA	Popular in the UK
Coagulants	Possible post-precipitation	NA	Utilities may be reluctant to vary coagulant feed (type and quantity)

Chlorine (pulsed)	NA	Limits on upper and lower chlorine residuals	Non-conservative and affected by wall demand

Note: NA indicates that research needs have not yet been identified.

Models

Mathematical models that represent the hydraulic behavior of the movement of water have been used to estimate water age in distribution systems (Clark and Grayman, 1998). Steady-state travel time models were first introduced in the mid-1980s (Males et al., 1985). These models were subsequently extended to dynamic representations that determined varying water age throughout the distribution system (Grayman et al., 1988). Water quality models can be used in conjunction with hydraulic models to predict concentrations of chlorine, DBPs, and other constituents in a distribution system (Vasconcelos et al., 1996). The effect of interaction of the flowing water with the pipe wall can be estimated using relationships proposed by Rossman et al. (1994). For each non-conservative water quality parameter, rates and mechanisms of reaction (decay and growth) must be identified and measured for a particular system.

Careful calibration of both hydraulic and water quality models is needed to generate an accurate prediction of water age and water quality conditions under varying demand scenarios. Typically, hydraulic and water quality conditions must be measured simultaneously since the changes in water quality are directly related to hydraulic and system operation conditions. Where feasible, hydraulic and facility operational information may be provided by the SCADA system. In addition, a calibration program may use existing chlorine monitor outputs. Where automated data is unavailable at facilities, manual data collection may be necessary.

Models may be limited in their ability to accurately predict water age for the following reasons:

- Skeletonization: Skeletonization may be needed if the water system contains more pipe segments than the model can handle. While the physical distance between two nodes is maintained in a skeletonized model, smaller diameter pipes (8-inch) may be excluded. The impact of skeletonization on the accuracy of water age predictions will vary from system to system, depending on the proportion of smaller diameter pipes compared to the overall number of pipes in the system and the piping configuration.
- Insufficient calibration: Typical calibration just looks at a single time step and does not look at extended period analysis. If there is a small error in the single step or if the pump operation is not exactly right, the flows throughout the system may not be accurately represented.
- Water Storage Tanks: Tanks are modeled as completely mixed reactors in most models. This typically leads to an underestimation of the water age. Reservoir mixing is addressed in more detail in the Finished Water Storage Facilities White Paper.
- Inaccurate total demand or demand allocation: If the overall demand is miscalculated it could result in more/less source and reservoir operation than actually occurs. It could also lead to more/less water crossing a system than actually occurs.

- Errors in Model Development: Inaccurate settings on PRVs or pump curves would limit the accuracy of water age analysis.

Because water age calculations require extended period simulations and include more complex analysis of the water system than do typical modeling exercises, the chances of inaccuracy increase.

A simplified model of water age in tanks and reservoirs was developed in the early 1990s (Grayman and Clark, 1993) and later refined as part of an AwwaRF study entitled "Water Quality Modeling of Distribution System Storage Facilities" (Grayman et al., 2000). In that study, more complex computational fluid dynamics (CFD) models that represent the hydrodynamic behavior were also applied to tanks and reservoirs. Methods were designed to provide estimates of the mixing characteristics, and the distribution and concentration of conservative constituents (or substances that decay according to a first-order decay function) to predict water age within a reservoir.

4.2 Design

Standard design guidelines for hydraulic considerations in the planning and design of distribution system piping networks are available in:

- Recommended Standards for Water Works (Ten State Standards, 1997)
- Guidance Manual for Maintaining Distribution System Water Quality (AwwaRF, 2000)
- Sizing Water Service Lines and Meters (AWWA M22, 1975)
- Distribution System Requirements for Fire Protection (AWWA M31, 1998)
- State regulations

Design guidelines for sizing storage facilities are discussed in the Finished Water Storage Facility White Paper.

4.3 Operations

Operations practices can impact flow direction, flow velocity, and water age. The water's hydraulic path and resulting detention time are affected by distribution system valve settings and pump station operations. Closing distribution system valves (purposefully or accidentally) can result in dead-ends with out proper blow-offs. In an effort to reduce hydraulic retention times, the utility may modify pressure zone boundaries or pressure set points at pumping stations. With these changes, it is important to assure that a minimum pressure of 20 psi is maintained at all locations at all times, and that service dependability is maintained.

Additionally, reservoir operations can significantly impact water age and associated water quality decay as discussed in the White Paper on Finished Water Storage. Increased water age within reservoirs is usually attributed to under utilization and/or poor mixing. According to Grayman et al. (2000), a measure of the mixing in a reservoir is the time it takes for the contents of the reservoir to become relatively well mixed following a change in the inflow concentration of a constituent of tracer. Based on empirical work for utilizing a scale model, the relationship shown in Equation 2 was developed for cylindrical tanks under fill and draw operation:

Mixing time (in seconds) = $9\ V^{2/3}\ (d/Q)$ (Eq. 2)

Where:

V = volume of water in tank at start of fill (cubic feet)
Q = inflow rate (cubic feet per second)
d = inlet diameter (feet)

Mixing time is highly dependent on the inflow rate and quantity of water flowing into the reservoir. Often, mixing can be increased by operating a reservoir so that the inflow rate is increased. Additionally, daily turnover rates (inflow/outflow quantity) can be increased to reduce overall water age.

4.4 Maintenance

Water system flushing is an important tool for helping to keep the water system clean and free of sediment, and to remove stagnant water.

Utilities can also clean or replace deteriorated pipelines that are known to be contributing to bulk water quality decay. A variety of pipeline cleaning techniques are utilized including mechanical scraping, pigging, swabbing, chemical cleaning, and flow jetting. Each technique has it benefits and drawbacks and should be tailored to the specific site. Depending on the cleaning technique used, relining of the pipeline may be necessary to prevent accelerated corrosion.

4.5 Source Water Treatment

Source water treatment can help mitigate many of the water quality problems associated with increased water age by improving the biochemical stability of finished water. With enhanced stability, the rates and extent of many chemical and biological reactions are suppressed.

Biochemical stability is closely related to the amount and speciation of organic matter in water. Over time, natural organic matter reacts with disinfectants to produce DBPs. Biodegradable and assimilable organic carbon provide energy and biomass which support the proliferation of microbial communities. The removal of these precursors during treatment precludes the ability of many of these reactions to occur, regardless of water age. Common treatment practices include enhanced coagulation, biological filtration, ultra- or nanofiltration, and granular activated carbon filtration. Ozone may be used as a primary disinfectant to convert organic carbon to a form that is more readily biodegraded by microbes in biological filters. Enhanced coagulation is specified as a best available technology in the D/DBP Rule for removing natural organic matter.

Treatment to remove organics, inorganics, and turbidity will also curb the rate of chlorine decay, thus allowing a higher residual to reach further into the system and persist longer.

pH stability is important in minimizing DBP formation. Without the appropriate level of source water treatment, the pH in some systems may vary by up to two pH units. pH variability may be reduced by increasing source water alkalinity and buffer intensity.

Iron corrosion in unlined cast iron pipe can contribute to the water's chlorine demand. Corrosion may be controlled with pH and alkalinity adjustment or addition of a corrosion inhibitor such as polyphosphate or addition of calcium.

Treatment to remove iron and manganese can help to reduce the sediment load in pipelines and storage facilities. Treatment alternatives for iron and manganese removal include oxidation/filtration processes, oxidation/adsorption process, lime softening, and caustic soda softening.

The relationship between water age and temperature cannot be altered with source water treatment.

4.6 Indicators of High Water Age

There are several indicators that may suggest high water age. These include aesthetic considerations that may be identified by consumers, as well as the results of distribution system monitoring efforts. It should be noted that indicators can be triggered by factors other than water age, such as insufficient source water treatment, pipe materials, and condition/age of distribution system.

Aesthetic Indicators

The following indicators may be identified during water consumption:

- Poor taste and odor – Aged, stale water provides an environment conducive to the growth and formation of taste and odor causing microorganisms and substances.
- Discoloration – Water in low flow areas and dead-ends often accumulate settled deposits over time. During a demand period, these deposits are entrained and degrade the clarity and color of the water.
- Water temperature – Stagnant water will approach the ambient temperature.

Monitoring Indicators

The following indicators require sample collection and analysis:

- Depressed disinfectant residual – Chlorine and chloramines undergo decay over time.
- Elevated DBP levels – The reaction between disinfectants and organic precursors occur over long periods.
- Elevated bacterial counts (i.e., heterotrophic plate count).
- Elevated nitrite/nitrate levels (nitrification) for chloraminating systems.

5.0 Summary

Water age is a major factor contributing to water quality deterioration within the distribution system. Water age is primarily controlled by system design and system demands. Thus, water age can vary significantly within a given system. Increased temperatures typically associated with increased water age can cause reactions to proceed faster and go further. Water quality problems that can be exacerbated by increased water age include DBP formation, decreased corrosion control effectiveness, nitrification, and microbial growth/regrowth. The Stage 1 and proposed Stage 2 DBP Rules recognize the relationship between DBP occurrence and water age, and have established monitoring requirements based on this link. The Lead and Copper Rule requires utilities to maintain optimal water quality parameters within the distribution system to ensure effective corrosion control treatment. For poorly buffered waters, increased water age can impact compliance with water quality parameter requirements. Potential health issues associated with Nitrification and Microbial Regrowth are addressed in separate White Papers. Tools for evaluating water age include hydraulic models, tracer studies, and monitoring programs. Existing AwwaRF and AWWA manuals provide guidelines for considering water age during design, operation, and maintenance of distribution system facilities. The objective of a new AwwaRF Study (#2769) entitled "Evaluating Retention Time to Manage Distribution System Water Quality" is to evaluate the feasibility and effectiveness of using distribution system retention time (or water age) as a tool for managing distribution system water quality.

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