

Water Quality in Distribution Systems



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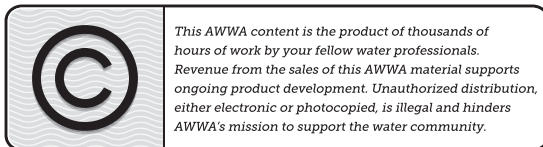
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Contents

List of Figures, vii

List of Tables, xi

Acknowledgments, xv

Chapter 1	Introduction	1
	Getting Started—How to Identify a Problem or Challenge, 2	
	Summary of Standards and Regulations, 6	
	References, 11	
Chapter 2	Capacity and Water Age.....	13
	Determining Capacity, 14	
	Determining Water Age, 21	
	Ways to Balance Capacity and Water Age, 24	
	Best Practices for Optimizing Distribution System Capacity and Water Age, 35	
	References, 37	
Chapter 3	Understanding and Managing Biofilm, Coliform Occurrence, and the Microbial Community	39
	Microbial Growth Challenges in the Distribution System, 40	
	Summary of Regulatory Frameworks Applicable to Microbes in Distribution Systems, 50	
	Microbial Occurrence Pathways, 52	
	Microbial Indicators of Water Quality, 54	
	Techniques for Characterizing Microbial Communities, 60	
	Contributing Factors, Mitigation, and Corrective Actions for Microbial Occurrence Problems, 62	
	Best Practices to Mitigate and Manage Microbial Growth, 69	
	References, 71	
Chapter 4	Infrastructure Integrity and Water Quality.....	81
	Factors That Affect Physical Integrity, 82	
	Factors That Affect Water Quality, 84	
	Water Quality Indicators, 86	
	Addressing Water Quality Challenges, 86	
	Best Practices, 88	
	References, 97	
Chapter 5	Taste, Odor, and Appearance.....	101
	Aesthetic Water Quality Goals, 103	
	General Identification and Monitoring of Water Quality Aesthetics in Distribution Systems, 103	
	Taste and Odor, 110	
	Appearance, 125	
	Summary and Recommendations, 131	
	References, 133	

Chapter 6	Nitrification.....	151
	Disclaimer, 151	
	Nitrification, 152	
	Causes of Nitrification in Distribution Systems, 155	
	Examples of Nitrification, 163	
	Responses to Control Nitrification, 167	
	Nitrification Monitoring and Control Plan, 173	
	Nitrification Prevention, 180	
	Case Study, 185	
	Conclusions and Recommendations, 186	
	References, 188	
Chapter 7	Corrosion Control.....	195
	Water Quality Impacts, 196	
	Factors Affecting Corrosion-Related Water Quality, 201	
	Water Quality Monitoring, 210	
	Corrosion Control Methods, 216	
	Best Practices for Corrosion Control Through Distribution System Design, Operation, and Maintenance, 218	
	Summary, 225	
	References, 227	
Chapter 8	Disinfectants and Disinfection By-products.....	233
	Regulations, 234	
	Disinfectants, 239	
	Control Strategies, 248	
	Best Practices, 256	
	Summary, 258	
	References, 260	
Chapter 9	Management of Low Pressure.....	267
	Pressure Standards and Goals, 268	
	Causes of Depressurization and Intrusion, 269	
	Public Health Impact of Depressurization-Related Water Quality Problems 271	
	Tracking Depressurization-Related Water Quality Challenges, 274	
	Preventing and Managing Low Pressure, 283	
	Distribution System O&M, 288	
	Three-Integrity Approach, 291	
	Case Studies, 295	
	Summary and Recommendations, 298	
	References, 300	
Chapter 10	Cross-Connection Control and Backflow Prevention.....	305
	Backflow and Hydraulic Principles, 306	
	Examples of Backflow and Cross-Connection Incidents and Their Effects on Water Quality, 309	
	Indicators of a Backflow Incident, 311	
	Responding to Backflow Incidents, 313	
	Best Practices, 315	
	Additional Resources, 318	

	The Future: What Emerging Technologies Will Have an Effect on Backflow As a Water Quality Risk for Utilities?, 318	
	References, 319	
Chapter 11	Security Issues.....	321
	Introduction, 321	
	Potential Threats and Pathways, 322	
	Contaminant Detection, 324	
	Responding to Contamination Threats and Events, 329	
	Risk Assessment and Planning, 330	
	Summary, 333	
	References, 335	
Appendix A	Techniques to Characterize Microbial Communities.....	339
Appendix B	Summary of Flushing Techniques, Likely Water Quality Responses, and Potential Applications	351
Appendix C	Methods for Identifying and Monitoring Water Quality Aesthetics in Distribution Systems	355
Appendix D	Nitrification Monitoring Plan.....	369
	Glossary, 373	
	Index, 411	
	AWWA Manuals, 423	

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Figures

- 2-1 Pump and system head curves, 15
- 2-2 Distribution system storage volume design concept, 19
- 2-3 Example of how storage tank mixing characteristics affect tank water age effluent, 22
- 2-4 Increasing disinfection by-products with water age in a free-chlorinated system, 27
- 2-5 Example of chloramine bulk decay curve, 28
- 2-6 Example improvements in water age by controlling pump speed by flow or tank level, 30
- 2-7 Tuberculated pipe with reduced capacity, 31
- 2-8 Example of diminishing returns on water age from flushing rates, 34
- 3-1 Comparison of bacterial abundance (biomass as inferred from adenosine triphosphate content of living cells) of different phases within a 1-m water main (polyvinyl chloride, 110 mm), 42
- 3-2 Number of waterborne disease outbreaks associated with drinking water (N = 851), by year and etiology—United States, 1971–2012, 48
- 3-3 Deficiencies assigned to (A) drinking water outbreaks (N = 32) and (B) outbreak-related cases (N= 431) from the Waterborne Disease and Outbreak Surveillance System, 2011–2012, 48
- 3-4 Importance of the heterotrophic plate count method: standard plate count agar versus Reasoner’s 2A agar, 60
- 3-5 Scheme showing the different techniques available to characterize microbial communities in drinking water distribution systems, 61
- 3-6 Examples of scales formed on (A) unlined cast-iron, (B) cement-lined ductile-iron, and (C) plastic piping materials, 63
- 4-1 Progression of accumulation and release of pipe materials, 85
- 5-1 Drinking water taste-and-odor wheel, 107
- 5-2 Simplified taste-and-odor wheel for drinking water, 108
- 5-3 Exceedance plots for the total number of water quality complaints that occurred per day, week, and month (28 days), 109
- 6-1 *Nitrosomonas* species isolated from a drinking water reservoir; transmission electron micrograph (bar, 0.1 μm), 154
- 6-2 Simplified *Nitrosomonas europaea* central metabolism, 154
- 6-3 US minimum total chlorine residuals in distribution systems (not at entry points to the distribution system), by state, for Subpart H Surface Water Treatment Rule systems. Information is based on a review of existing states’ rules and regulations as of January 2015, 158

- 6-4 Monochloramine decay as a function of Cl/N molar ratio. Cl/N = 0.5 (□, ■) Cl/N = 0.6 (○, ●), and Cl/N = 0.7 (△, △). Open symbols are for pH ≈ 7.5 and filled symbols are for pH ≈ 6.5. [NH₂Cl] = 0.05 mM, C_{T, CO₃} = 4 mM, μ = 0.1 M, temperature = 25°C. 0.05 mM NH₂Cl = 3.55 mg Cl₂/L, 160
- 6-5 Effect of pH on monochloramine decay at 25°C. 0.05 mM NH₂Cl = 3.55 mg Cl₂/L, 161
- 6-6 Effect of total carbonate on monochloramine decay at (A) pH ≈ 6.6, (B) pH ≈ 7.6, and (C) pH ≈ 8.3. Cl/N = 0.7 mol/mol, μ = 0.1 M, temperature = 25°C. 0.05 mM NH₂Cl = 3.55 mg Cl₂/L, 162
- 6-7 Effect of temperature on monochloramine decay. Cl/N = 0.7 mol/mol, pH = 7.5, C_{T, CO₃} = 10 mM, μ = 0.1 M. 0.05 mM NH₂Cl = 3.55 mg Cl₂/L, 163
- 6-8 Effect of 0–3 mg/L bromide ion on monochloramine stability at pH ≈ 7.5. Cl/N = 0.7 mol/mol, C_{T, CO₃} = 4 mM, μ = 0.1 M, temperature = 25°C. 0.05 mM NH₂Cl = 3.55 mg Cl₂/L, 163
- 6-9 Theoretical water quality changes during a nitrification event, 165
- 6-10 Example of complete nitrification in a Massachusetts Water Resources Authority distribution system, 166
- 6-11 Example of storage tank breakpoint chlorination procedure, 169
- 6-12 Impact of tank draining and disinfecting on nitrification, 170
- 6-13 Theoretical breakpoint curve, 171
- 6-14 Free chlorine period survey results, 172
- 6-15 Example of system-wide breakpoint chlorination protocol, 172
- 6-16 Total chlorine residual as a function of time at various distribution system sampling locations, 176
- 6-17 Changes in chlorine concentrations with water age in a distribution system, 177
- 6-18 Common water system actions to control nitrification from a 2004 survey, 180
- 6-19 Example of storage tank stratification occurrence and assessment, 183
- 6-20 Effectiveness of booster chloramination in reducing nitrite formation at Key West Utility, 185

- 7-1 Red water sample from a US water distribution system, 200
- 7-2 Oxidation-reduction potential of common oxidants at various dosages, 206
- 7-3 Pourbaix diagram for lead, 207
- 7-4 Pourbaix diagram for copper, 207
- 7-5 Pourbaix diagram for iron at 25°C and 4.8 mg/L dissolved inorganic carbon, 208
- 7-6 Correlations (R² values) between trace inorganic compound release in two water systems' distribution systems, 209
- 7-7 Calcium carbonate precipitation in a distribution main, 213
- 7-8 Mini pipe loops, 222
- 7-9 Metal plates inside and stacked in open test chambers, 223
- 7-10 Process control charts for historical disinfection data at two Revised Total Coli-form Rule sampling sites, 224

- 7-11 Example of pipe before and after cleaning and lining with cement–mortar, 226
- 7-12 Steel pipe lined with epoxy, 226

- 8-1 Main pathways involved in the formation of ozone by-products, 244
- 8-2 Example of the correlations between water age, trihalomethanes, and disinfectant residual in distribution systems, 249
- 8-3 Example of correlations between water age, haloacetic acids, and disinfectant residual in distribution systems, 250
- 8-4 Effect of cycling spray nozzle aeration (on/off) on trihalomethane level in a 0.5-mil gal clearwell in Madison, North Carolina, 252

- 9-1 Example of a pressure transient, 270
- 9-2 Water system power outages per year, 272
- 9-3 Examples of potential intrusion sites: (a) broken main near sewer pipe, (b) broken main near storm pipe, and (c) flooded meter vault, 272
- 9-4 Example field installations of pressure monitors in distribution systems, 276
- 9-5 Example output of the spreadsheet program for pressure monitoring, 278
- 9-6 Pressure transient control and management in (a) large zones and (b) small zones of 36 surveyed systems, 287
- 9-7 Location of boil-water advisories in the United States, 291
- 9-8 Modeled minimum pressure in an Illinois water system during a power outage at the primary pump station, 296
- 9-9 Backflows and low pressure event caused by main break: (a) broken main, back-flow locations, and modeled negative pressures; (b) pressure drop at the two optimized pressure monitoring locations; and (c) water usage increase during the main break, 297

- 10-1 Absolute, atmospheric, gauge, and vacuum pressures, 308
- 10-2 Example of a barometric loop, 309
- 10-3 Diagram of the Venturi effect, 310

- 11-1 Contamination warning indicators, 325
- 11-2 Steps in the ANSI/AWWA Standard J100 risk assessment process, 332

- A-1 Importance of heterotrophic plate count method (plate count agar versus R2A), 341

- D-1 Nitrification assessment flowchart, 369
- D-2 Total chlorine residual as a function of time at various distribution system sampling locations, 371

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Tables

1-1	M68 chapters and their focus, 2
1-2	Chapters on microbial activity and disinfectant residual challenges, 5
1-3	Chapters on disinfection by-products challenges, 5
1-4	Chapters on internal corrosion challenges, 5
1-5	Customer complaint issues, 6
1-6	Summary of USEPA distribution system regulatory requirements and monitoring, 7
1-7	Summary of Health Canada distribution system guidelines and monitoring, 9
2-1	Typical pipe capacity design criteria, 16
2-2	Example diurnal pattern and equalizing storage volume calculation, 19
2-3	Water quality evaluation criteria for balancing system capacity and water age, 36
3-1	Recognized and potential enteric and water-based microbial pathogens to manage community drinking water risks, 47
3-2	US Safe Drinking Water Act regulations related to microorganisms in the distribution system, 51
3-3	Microbial parameters and use as indicators, 56
3-4	Best practices to control microbial growth, 70
4-1	Pipeline life expectancy benchmarks, 82
4-2	Leak detection methods, 90
4-3	Recommended leak detection method based on type of pipe, 90
4-4	Examples of wall thickness measurement methods, 91
4-5	Common rehabilitation methods, 94
4-6	Best practices to mitigate aging infrastructure, 95
5-1	Regulations for drinking water aesthetics for the World Health Organization, European Union, Canada, and the United States, 104
5-2	Odor threshold and descriptors for volatile inorganic and organic sulfur compounds, 111
5-3	Compounds that cause chlorinous, ozonous, and medicinal tastes and odors in water, 113
5-4	Odorous chemicals that leach from polymer pipes and have or may have regulatory limits, 115
5-5	Taste characteristics and regulations of major components in waters, 123
5-6	Common descriptions and potential sources of discolored water events, 128
5-7	Recommended practices to address taste, odor, and appearance issues, 131

6-1	Water chemistry impact of ammonia and nitrite oxidation by AOB and NOB per milligrams of ammonia-nitrogen per liter, 153
6-2	Usefulness, alert levels, and action levels of total chlorine at various locations of the distribution system, 178
6-3	Example of goals, alert levels, and action levels applied by Loudoun Water at distribution system monitoring locations, 179
6-4	Recommended practices for nitrification control, 187
7-1	Primary corrosion-related mechanisms that influence distribution system water quality, 197
7-2	International water quality standards for corrosion-related compounds, 197
7-3	Corrosion properties of materials frequently used in water distribution systems, 202
7-4	Assessment of common corrosion-related water quality impacts, 203
7-5	Summary of USEPA Lead and Copper Rule sampling requirements for water quality parameters, 211
7-6	Water quality characteristics related to corrosion factors, 220
7-7	Multilevel water quality parameters for a water system that uses chloramine and a phosphate-based inhibitor, 221
7-8	Recommended practices to address corrosion issues, 227
8-1	Factors that affect disinfectants and the fate of disinfection by-products in distribution systems, 235
8-2	Regulated disinfectants and disinfection by-products, 237
8-3	Haloacetic acids currently regulated and considered for regulations, 239
8-4	Advantages and disadvantages of free chlorine, 240
8-5	Advantages and disadvantages of chloramines, 242
8-6	Advantages and disadvantages of chlorine dioxide, 243
8-7	Advantages and disadvantages of ozone, 245
8-8	Advantages and disadvantages of ultraviolet light, 245
8-9	Advantages and disadvantages of advanced oxidation processes, 246
8-10	Entities that affect disinfectants and disinfection by-products in distribution systems and that could be included in a monitoring program, 257
8-11	Best practices to preserve disinfectant stability and minimize disinfection by-products, 259
9-1	Improvement planning for surge mitigation options, 296
9-2	Best practices for management of low pressures, 299
10-1	Summary of reported cross-connections and backflow incidents, 312
10-2	Summary of best practices related to cross-connection control, 317
11-1	Recommended best practices to address security challenges, 334

A-1	Summary of microbiological methods, 343
C-1	Matching sensory testing methods to water quality and treatment objectives, 359
C-2	Particulate matter that may be found in distribution systems that will likely result in customer complaints, 360
C-3	Comparison of different methods for evaluating geosmin and 2-methyl-isoborneol, 363

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Chapter **1**

Introduction

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A drinking water distribution system is a system of pipes that carry potable water from treatment plants or water sources to consumers. It is also the last barrier available to water systems to maintain safe and high-quality water. This manual presents typical distribution system water quality challenges, providing summaries of typical responses and best practices as a “first stop” for drinking water system professionals.

Since each distribution system is unique, this manual is not intended to be all inclusive. Rather, it is a guide that summarizes the issues and actions to be taken when distribution system issues arise and provides references to other industry standards and publications that provide more detail. Additionally, this manual does not delve into treatment process or source water changes that can affect the quality of water that enters the distribution system. Readers are encouraged to familiarize themselves with the American Water Works Association (AWWA) standards and manuals of practice related to water source and treatment. These manuals are available for purchase online at <http://www.awwa.org/publications/manuals-of-practice.aspx> (accessed May 16, 2016).

For purposes of this manual, distribution systems include pump stations, ground and elevated storage tanks, potable water mains, potable water service lines, and all associated valves, fittings, and meters. Potable water customer service lines are excluded (Texas Commission on Environmental Quality 2015).

The chapters in this manual are organized based on the most common distribution system challenges that water systems face today. These are listed in Table 1-1.

Each chapter provides an introduction and description of a Distribution System Water Quality (DSWQ) Challenge, followed by:

- Discussion and description of the factors associated with each challenge. See text box(es) in each chapter for a summary of Characterizing the DSWQ Challenge;

Table 1-1 M68 chapters and their focus

Chapter	Title
2	Capacity and Water Age
3	Understanding and Managing Biofilm, Coliform Occurrence, and the Microbial Community
4	Infrastructure Integrity and Water Quality
5	Taste, Odor, and Appearance
6	Nitrification
7	Corrosion Control
8	Disinfectants and Disinfection By-products
9	Management of Low Pressure
10	Cross-Connection Control and Backflow Prevention
11	Security Issues

- Summaries of available response actions. See text box(es) in each chapter for a summary of Responding to the DSWQ Challenge; and
- Recommended best practices for optimizing DSWQ. See the table in each chapter that lists DSWQ Best Practices, which are rated as “basic” or “advanced.” Some chapters include specific definitions for these terms. Generally, basic practices are the actions all water systems should perform if they have experienced the DSWQ challenge noted. Advanced practices are for water systems that wish to optimize and/or develop a comprehensive program related to the specific DSWQ challenge. Some chapters include an intermediate, or “moderate,” rating that is clearly defined within that chapter.

GETTING STARTED—HOW TO IDENTIFY A PROBLEM OR CHALLENGE

Understand Baseline Water Quality Conditions

Many water systems have developed acceptable ranges for various water quality parameters in their distribution systems, for example, pH, disinfectant residual, iron, and manganese. These ranges are based on regulatory requirements and specific utility goals. Some have also developed target levels that trigger various responses, such as notifying the water quality manager and taking action (e.g., flushing) to restore water quality to acceptable levels.

AWWA Standard G200-09, *Distribution Systems Operations and Maintenance* (AWWA 2010), provides guidance to help water systems establish the documented programs and practices needed to understand water quality problems in their distribution systems. In addition to meeting regulatory requirements and preparing written sampling plans, the utility should annually review sampling plans and make adjustments based on historical data trends (AWWA 2010). All AWWA standards are available at <http://www.awwa.org/publications/standards.aspx> (accessed May 16, 2016).

Customer complaint data can also help a utility identify the source and extent of a water quality problem if the complaint information is managed properly and is accessible. Standard G200 recommends that a utility have a system for documenting customer inquiries that includes the date, inquiry type, customer location, sampling results, and resolution (AWWA 2010).

Water systems that wish to take a holistic approach to the improvement of overall distribution system water quality should consider joining AWWA's Partnership for Safe Water. This is a voluntary optimization program that provides various tools and guidance for tracking disinfectant residual, pressure, and main breaks, as well as a self-assessment guide for systems that wish to optimize distribution system operations.

Some water systems have also implemented proactive quality assurance practices by using hazard analysis and critical control points (HACCP) programs in order to ensure higher levels of tap water safety. HACCP is a systematic preventive approach, designed in the 1960s to protect food and beverages from microbiological hazards. For drinking water systems, the HACCP system promotes a "source to tap" philosophy in order to identify the critical points throughout the entire system (i.e., those points within the system or its operation whose disruption or failure would result in a greater public health risk compared to other points) and then to focus resources on these critical locations and processes. This systematic approach helps water systems identify potential hazards that are closer to their source, thus minimizing the occurrence and effects of incidents that degrade water quality and potentially threaten public health (USEPA 2006).

Consider Regulatory and Policy Frameworks

Legislative frameworks should support effective management of drinking water quality. These frameworks vary throughout the world based on constitutional settings. Legislation should define the roles and responsibilities of the primary agencies and entities associated with ensuring the delivery of safe drinking water.

Drinking water quality regulation requires public health and treatment technology expertise, which typically resides within governmental health and/or environmental protection agencies. Local government environmental health officers may also assist in the administration of legislation. Irrespective of the identities of regulators, they need to be given sufficient power to monitor and enforce legislative requirements. In the United States, for instance, the Safe Drinking Water Act (SDWA) provides authority to the US Environmental Protection Agency (USEPA) to set national drinking water regulations, with enforcement potentially including national, regional, and local authorities. Summaries of US and international regulations are provided at the end of this chapter. It is important to note that in the United States, each primacy agency (USEPA region, state, or territory) may have rules and regulations that local public water systems must follow.

In addition to legislation, provision of safe drinking water may be supported by standards and policies that apply to matters such as certification of water operators, water treatment chemicals, and distribution system materials and plumbing. These can take the form of mandatory requirements or recommended practices (Cunliffe 2014).

A summary of current international and US regulatory and standard frameworks associated with distribution systems is included at the end of this chapter. Most have common themes, which include most or all of the following five categories of distribution water quality indicators:

- Microbial activity,
- Disinfectant residuals,
- Disinfection by-products (DBPs),
- Corrosion, and
- Aesthetics.

Microbial activity and disinfectant residuals. Many potential factors associated with microbial activity and loss of disinfectant residual are similar and, therefore, characterized together. Microbial growth in the distribution system can cause changes to drinking water quality that can adversely affect public health. Direct microbiological indicators are generally based on the presence or absence of bacteria, the most common include total coliforms, fecal coliforms, *Escherichia coli*, and heterotrophic plate count bacteria. The presence of these bacteria may indicate the potential existence of a pathogen or issues associated with the treatment process, distribution system integrity, and/or distribution system operations and maintenance. Chapter 3, Managing Biofilm, Coliform Occurrence, and the Microbial Community, provides a summary of the regulatory frameworks associated with these indicators, as well as information on each indicator.

Disinfectants in drinking water are used to control microbial growth and the potential hazards associated with that growth. Chlorine-based disinfectant residuals have both minimum and maximum regulatory limits. Chapter 8, Disinfectants and Disinfection By-products, discusses these types of disinfectants and summarizes the regulatory frameworks associated with them.

Chapters 3 and 8 provide information on the indicators and possible hazards associated with these indicators. These chapters should be used as starting points for water systems in the detection of microbial indicators and/or loss of disinfectant residuals. However, the contributing factors or root causes for the presence of these indicators can be found in other chapters of this manual. Table 1-2 summarizes potential contributing factors for the presence of microbiological indicators and loss of disinfectant residual in the distribution system, as well as other chapters that provide more information on these factors.

Disinfection by-products. DBPs are chemicals that form when disinfectants/oxidants react with organic and inorganic substances in the water. Several DBPs are currently regulated based on potential health effects, and water systems should focus on controlling the levels of these regulated compounds. Chapter 8, Disinfectants and Disinfection By-products, provides information on these currently regulated DBPs, as well as emerging compounds, in terms of the regulatory framework and health effects. Chapter 8 also provides information on the DBPs that are associated with different types of disinfectants used by water systems. Table 1-3 lists the chapters that include information on changing DBP levels in distribution systems.

Lead, copper, and other corrosion indicators. USEPA promulgated the Lead and Copper Rule (LCR) in 1991 to reduce consumer exposures to lead and copper in drinking water (56 FR 26460; *Federal Register* 1991). The purpose of the LCR framework is to protect public health by minimizing lead and copper levels in drinking water, primarily by reducing water corrosivity (USEPA 2004). Health Canada's Water Quality and Health Bureau also has developed guidelines for lead and copper. Table 1-4 lists the chapters that include information on internal corrosion challenges.

Aesthetics. In the United States, the USEPA sets secondary standards related to constituents that cause unpleasant aesthetic conditions in distribution systems. Customer complaints are an initial indicator for aesthetic issues. These are typically related to color, taste, odor, particles, pressure, and sometimes perceived or actual sickness. AWWA Standard G200 recommends use of action plans to address color and staining, as well as taste and odor inquiries (AWWA 2010). Many customer complaints can be attributed to the factors listed in Table 1-5.

Table 1-2 Chapters on microbial activity and disinfectant residual challenges

Potential Contributing Factor	Relevant Chapter(s)
Microbial growth, pathogen presence	Chapter 3, Understanding and Managing Biofilm, Coliform Occurrence, and the Microbial Community
Disinfectant residual	Chapter 8, Disinfectants and Disinfection By-products
Aged water	Chapter 2, Capacity and Water Age
Main breaks	Chapter 4, Infrastructure Integrity and Water Quality Chapter 9, Management of Low Pressure
Nitrification	Chapter 6, Nitrification
Unprotected cross-connections	Chapter 10, Cross-Connection Control and Backflow Prevention
Contamination	Chapter 11, Security Issues

Table 1-3 Chapters on disinfection by-products challenges

Potential Contributing Factor	Relevant Chapter(s)
Changes in disinfectant and/or source water organic content	Chapter 8, Disinfectants and Disinfection By-products
Aged water	Chapter 2, Capacity and Water Age

Table 1-4 Chapters on internal corrosion challenges

Potential Contributing Factor	Relevant Chapter(s)
Inadequate corrosion control	Chapter 7, Corrosion Control
Contamination event evidenced by pH/alkalinity variations	Chapter 10, Cross-Connection Control and Backflow Prevention Chapter 11, Security Issues
Change in disinfectant or treatment	Chapter 8, Disinfectant and Disinfection By-products
Microbial-induced corrosion	Chapter 3, Understanding and Managing Biofilm, Coliform Occurrence, and the Microbial Community Chapter 6, Nitrification

Table 1-5 Customer complaint issues

Potential Contributing Factor	Relevant Chapter(s)
Corrosion	Chapter 7, Corrosion Control
Secondary and other constituents that cause aesthetic issues	Chapter 5, Taste, Odor, and Appearance
Main breaks	Chapter 4, Infrastructure Integrity and Water Quality Chapter 9, Management of Low Pressure
Microbial growth	Chapter 3, Understanding and Managing Biofilm, Coliform Occurrence, and the Microbial Community Chapter 6, Nitrification
Changes in disinfectants	Chapter 8, Disinfectants and Disinfection By-products

SUMMARY OF STANDARDS AND REGULATIONS

US Regulations

In the United States, Congress established the SDWA to protect the quality of drinking water throughout the nation. This law focuses on all waters actually or potentially designed for drinking use, whether from above ground or underground sources. SDWA authorizes USEPA to establish minimum standards to protect tap water and requires all owners or operators of public water systems to comply with these primary (health-related) standards (USEPA 2015). The 1996 amendments to the SDWA require that USEPA consider a detailed risk and cost assessment and best available peer-reviewed science when these standards are developed (USEPA 2015). USEPA also encourages attainment of secondary standards (nuisance-related; USEPA 2015).

The USEPA regulations that are based on the SDWA and its amendments are listed in Title 40 of the Code of Federal Regulations (CFR), which can be found at www.ecfr.gov (accessed April 26, 2016).

The SDWA, like most environmental regulations, is typically implemented through primacy agencies, where individual states or territories establish and enforce requirements that are at least as stringent as the federal requirements. Prior to the SDWA, states adopted US Public Health Service standards as regulations or guidelines (USEPA 1999). However, a 1970 survey of community water supplies revealed that 79 percent of systems were not being surveyed by state or local health departments (US Department of Health, Education, and Welfare 1970). The SDWA establishes and authorizes USEPA to allow states to assume primary oversight and enforcement, or primacy, for public water systems (Tiemann 2014).

According to Title 40 CFR regulations, primacy agencies have special requirements beyond implementation of the SDWA, which include ensuring that water systems are appropriately designed, constructed, and have appropriately certified operators based on water system size and water type.

Several SDWA requirements apply to the quality of water that enters distribution systems. There are also rules that apply to distribution systems, including the Total Coliform Rule, Surface Water Treatment Rules, Disinfectants/Disinfection Byproduct Rules, and Lead and Copper Rule. USEPA develops these regulations by setting acceptable public health standards based on the best available peer-reviewed science and what is feasible for water systems. To ensure these levels are met, USEPA regulations also set minimum monitoring requirements. Table 1-6 summarizes the current USEPA regulations that are associated with distribution systems, the public health requirement associated with distribution

system levels, and required monitoring. Some chapters in this manual contain more detailed information on regulations as related to specific DSWQ challenges.

Additionally, it is important to note that the USEPA released its third Six-Year Review (Six-Year Review 3) in December 2016. The SDWA requires the USEPA to review each national primary drinking water regulation at least once every six years and to revise them, if appropriate. As part of the Six-Year Review 3, USEPA identified the following eight contaminants as candidates for regulatory revision: chlorite, cryptosporidium, haloacetic acids, heterotrophic bacteria, giardia lamblia, legionella, total trihalomethanes, and viruses. Many of these contaminants are related to distribution system challenges and are reflected in chapters of this manual. The reader is encouraged to reference the USEPA website on the Six-Year Review 3 for the most current information (USEPA 2016).

Table 1-6 Summary of USEPA distribution system regulatory requirements and monitoring

Regulation	Distribution System Requirement	Monitoring
TCR and RTCR (USEPA 2014)	No more than 5 percent of samples positive for total coliform and no fecal contamination or <i>Escherichia coli</i> ; RTCR requires assessments for exceedances	Collect monthly samples at sites representative of the distribution system and population served
Surface Water Treatment Rules (USEPA 2004a)	At least 95 percent of distribution samples in water originating from a surface water source must have detectable residual*	Check residual disinfectant concentration at entry points to the distribution system and at TCR/RTCR routine sites
Disinfectant/Disinfection Byproduct Rules (USEPA 2006a)	Chlorine maximum residual disinfectant level (MRDL) = 4.0 mg/L; TTHMs and HAA5 locational running annual average maximum contaminant levels = 80 and 60 µg/L, respectively	Check residual disinfectant concentration at TCR/RTCR routine sites; measure TTHM and HAA5 quarterly in distribution system
Lead and Copper Rule (USEPA 1999a)	Lead levels must be <15 µg/L and copper levels must be <1.3 mg/L in 90 percent of samples [†]	First-draw tap samples for lead and copper every 6 months, annually, or every 3 years; alkalinity, pH, and corrosion inhibitor (if appropriate) monitoring every six months or annually

Abbreviations: HAA5, group of five haloacetic acids; TCR, Total Coliform Rule; TTHM, total trihalomethanes; RTCR, Revised Total Coliform Rule.

* Several states have rules regarding disinfectant residual requirements in distribution systems. Check with local primacy agencies for specific requirements.

[†] At the time this chapter was written, USEPA's National Drinking Water Advisory Council work group had finalized and made recommendations to revise the Lead and Copper Rule (LCR). These recommendations include proactive lead service line replacement, stronger public education, improved corrosion control treatment, tap sampling modifications, expanded water quality parameter monitoring, a household action level for lead, and separate requirements for copper. For more information on these recommendations and any subsequent proposed LCR changes, visit <http://www.epa.gov/dwreginfo/lead-and-copper-rule> (accessed April 26, 2016).

World Health Organization

The World Health Organization (WHO), an agency of the United Nations responsible for public health, developed a comprehensive set of guidelines related to drinking water quality that are intended to assist policymakers around the world to ensure sound drinking water practice. These nonenforceable guidelines have been established for various microbial, chemical, radiological, and aesthetic-based contaminants (WHO 2011). The WHO has also formalized a HACCP management approach, known as Water Safety Plans (WSPs; WHO 2009).

Australia

The National Health and Medical Research Council in collaboration with the National Resource Management Ministerial Council developed the Australian Drinking Water Guidelines in order to provide individual communities and regulatory agencies with a structure for proper treatment and management of drinking water supplies. The guidelines propose limits for microbial, physical, and chemical parameters in drinking water to ensure supplies are safe for human consumption. In addition, the guidelines include recommendations for selecting and monitoring the effectiveness of various treatment processes. These are nonenforceable standards. Each state or territory may choose to implement any or all of the guidelines. Readers are advised to consult the individual state or territory for additional information on drinking water requirements (NHMRC, NRMCMC 2011).

Canada

Health Canada's Water Quality and Health Bureau, on behalf of the Federal-Provincial-Territorial Committee on Drinking Water, is the federal organization responsible for developing the Guidelines to Canadian Drinking Water Quality (Health Canada 2014). Similar to maximum contaminant levels established in the United States, these guidelines are designed to protect public health by establishing maximum acceptable concentrations (MACs) for microbiological, physical, chemical, and radiological parameters in drinking water (Health Canada 2014). These are nonenforceable federal standards. In Canada, the establishment of drinking water legislation is the responsibility of the individual provinces and territories (Health Canada 2014).

Each province or territory may choose to adopt a portion or all of the MACs established under the Guidelines to Canadian Drinking Water Quality or to establish new levels. To date, only 2 of the 12 provinces and territories (Alberta and Nova Scotia) have adopted the Guidelines to Canadian Drinking Water Quality in their entirety as enforceable drinking water regulations (Health Canada 2014). In addition, each province or territory is responsible for developing a set of drinking water requirements related to treatment, monitoring, and reporting (Health Canada 2014). Alberta has also regulated the need for drinking water safety plans for each system, which follows the WHO's WSP management approach (Government of Alberta 1995–2015).

While the individual requirements vary across Canada, the overarching nationwide goal is to use a multibarrier approach to protect public drinking water by reducing or preventing contamination at the source, during treatment, and throughout the distribution system (Health Canada 2014). Table 1-7 summarizes some of the Health Canada guidelines that apply to distribution systems (Health Canada 2014).

Table 1-7 Summary of Health Canada distribution system guidelines and monitoring

Guideline	Maximum Acceptable Concentration (MAC)	Recommended Monitoring
Total coliform/ <i>Escherichia coli</i>	None detectable in a 100-mL sample leaving the treatment plant and in nondisinfected water leaving the well	For systems that serve up to and including 5,000 people: monitor water leaving pump house or treatment plant and at representative locations in the distribution system four times per month; no consecutive samples from the same site or not more than 10 percent of samples should show the presence of total coliform bacteria*
Chlorine	None required	Free and/or total chlorine residuals should be tested when bacteriological samples are taken*
Monochloramine	3.0 mg/L	Free and/or total chlorine residuals should be tested when bacteriological samples are taken*
Lead	0.010 mg/L	Option 1: two-tier protocol; tier 1, annual first draw, if 10 percent >0.015 mg/L, then tier 2: four consecutive 1-L sampling in highest 10 percent locations Option 2: lead service line residences; four consecutive 1-L sampling; site average <MAC in >90 percent of locations†
Trihalomethanes	0.10 mg/L for the sum of chloroform, chlorodibromomethane, bromodichloromethane, and bromoform	For systems that use chemical disinfection, monitor every three months to compute a locational running annual average of quarterly samples*
Haloacetic acids	0.08 mg/L as low as reasonably achievable; for the sum of monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid	For systems that use chemical disinfection, monitor every three months to compute a locational running annual average of quarterly samples*

* Health Canada Guidance for Providing Safe Drinking Water in Areas of Federal Jurisdiction, Version 2. Accessed May 16, 2016. <http://healthycanadians.gc.ca/publications/healthy-living-vie-saine/water-federal-eau/index-eng.php>.

† Health Canada Guidance on Controlling Corrosion in Drinking Water Distribution Systems. Accessed May 16, 2016. <http://healthycanadians.gc.ca/publications/healthy-living-vie-saine/water-corrosion-eau/index-eng.php>.

Emirate of Abu Dhabi

In 2009, the Regulation and Supervision Bureau for the Water, Wastewater, and Electricity Sector in the Emirate of Abu Dhabi developed the Water Quality Regulations to ensure that safe drinking water is provided to all customers throughout the Emirate of Abu Dhabi. The regulations establish maximum limits for select microbial, inorganic, and organic contaminants in drinking water based on WHO guidelines. The regulations include requirements for monitoring and recordkeeping for water suppliers. While the regulations do not directly discuss treatment or disinfection, they do state that “the water does not contain any element, organism or substance at a concentration or value which would be detrimental to public health” and contain limits for various DBPs (Regulation and Supervision Bureau 2009).

European Union

In 1998, the European Union (EU) issued Directive 98/83/EC, which established minimum standards for water intended for human consumption for EU Member States. Although disinfection is not explicitly required, the directive includes limits for microbiological parameters and DBPs that are similar to the WHO guidelines. Member States are also encouraged to minimize DBP formation, but not at the expense of disinfection. Member States may adopt stricter standards as well as limits for additional parameters. In general, most Member States require disinfection of surface waters using chlorine, chlorine dioxide, ozone, or ultraviolet light but do not require disinfection of groundwater supplies. Only some Member States require that a minimum disinfectant residual be maintained at all times in the distribution system. Other Member States, such as the Netherlands, apply strategies that include the use of only high-quality water supplies and biologically stable distribution system materials in addition to distribution system operational strategies such as flushing to minimize the potential for bacterial regrowth (EU Council 1998).

In October 2015, the European Commission adopted a directive to revise Directive 98/83/EC to include an option to perform monitoring in a more flexible way, provided a risk assessment is performed to ensure full protection of public health. It follows the principle HACCP and the WHO's WSP approach (European Commission 2015).

New Zealand

The New Zealand Water Quality Guidelines were developed based on WHO guidelines and include recommended maximum values for microbial, radiological, and chemical parameters, including DBPs. The guidelines are enforceable and apply to all drinking water providers regardless of source, treatment type, or distribution system size. The guidelines require that some form of disinfection be provided for all surface or spring water sources. The guidelines also include requirements for monitoring disinfection efficiency at treatment plants and in the distribution system in addition to reporting and corrective action requirements (Ministry of Health 2008).

Republic of South Africa

The South African Water Quality Guidelines were established in 1996 and provide target water quality ranges for various microbial, physical, chemical, and aesthetic parameters. The guidelines recommend disinfection via chlorination or chloramination and that an adequate residual be maintained to minimize any bacterial regrowth or biological corrosion (Department of Water Affairs and Forestry 1996).

Drinking water must also comply with the requirements set forth in the South African National Standard (SANS) 241 Drinking Water Specification. The specification establishes maximum allowable concentrations for select parameters monitored at the "point of delivery." Values have been established based on WHO guidelines (Department of Water Affairs and Forestry 1996).

Singapore

Recently, the Singapore Government promulgated the Environmental Public Health Act, which established standards for the quality of drinking water in piped systems. The act also includes information on development of sampling and safety plans. Although the act does not plainly require disinfection, the Public Utilities Board, which is the national water agency in Singapore, provides disinfection of its water supplies prior to distribution (Government of Singapore 2008).

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Chapter 2

Capacity and Water Age

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Historically, water distribution systems have been sized using a capacity-based approach, with future demand scenarios and economies of scale often driving sizing decisions. The main focus was on providing hydraulic reliability and maintaining positive pressures throughout the system (Kelley 1994). While these considerations are still critical to the function of a water distribution system, there is a general understanding now that the negative impacts to water quality when systems are oversized should also be considered in sizing system components. More recent trends include selecting the right-sized facility in the right location (Mays 2000).

Distribution system water quality may be characterized in a variety of ways, many of which are discussed throughout this manual. One general indicator of water quality in distribution systems is water age. Water age is defined as the average time it takes for water to travel from the treatment facility to any given point within the distribution system. In general, water quality tends to deteriorate with increasing water age. For example, disinfectant residuals decrease, microbial activity increases, and disinfection by-products (DBPs) increase as water increases.

With this increased awareness of the relationship between water age and water quality, water quality issues are no longer thought of as something to be addressed only at the treatment facility, nor can they be separated from the infrastructure and hydraulic issues that distribution systems face today.

DSWQ Challenge:

As water age increases, disinfectant residuals decrease, microbial activity increases, and disinfection by-products increase.

DETERMINING CAPACITY

The first step in evaluating a distribution system's water quality is to understand the existing system capacity. This includes setting appropriate design criteria and water age criteria for the system and then comparing existing conditions to the selected criteria. Design criteria vary from system to system depending on a variety of factors. This section reviews the basic steps and considerations in setting design criteria for the capacity of different distribution system components. Additionally, water age goals vary from system to system as a function of water quality goals, source water quality, treatment types, and other factors. This section also reviews water age goals considering these factors.

Design criteria for many systems have changed over the decades; the design criteria used for existing infrastructure is likely to differ from that to be used for new infrastructure. Changes in design criteria or changes in system demand over time result in facilities that are either under- or overdesigned with respect to current needs. This adds to the challenges many utilities face with respect to infrastructure investment.

In 2010, investment needs for buried drinking water infrastructure totaled more than \$1 trillion just within the United States over the succeeding 25 years (AWWA 2010). The World Bank estimated global infrastructure investment needs at \$35 trillion in the succeeding 20 years (HSNW 2010).

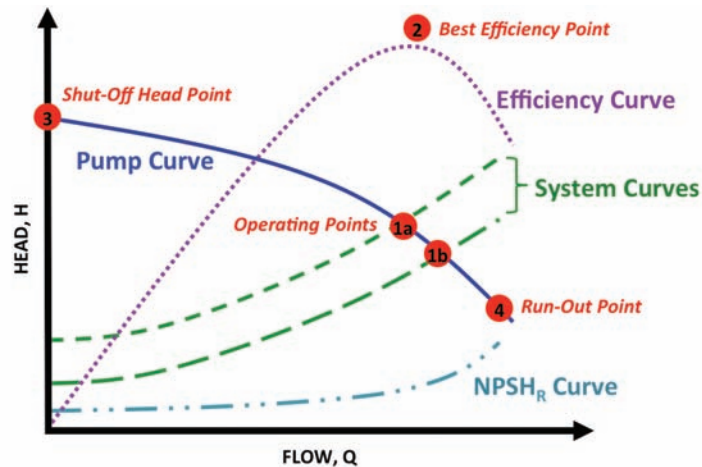
Today, prioritizing infrastructure renewal based on water age and water quality goals is more imperative than in previous decades in order to not only maintain water quality but make the best possible use of limited available funds for infrastructure renewal. Before making significant new investments, water quality in the distribution system must be considered. Use of objective methods to determine the capacity of existing infrastructure and water age in existing distribution systems is therefore an important first step toward evaluating design criteria. The following section reviews common methods to measure and/or estimate the capacity and water age of distribution systems.

Determining Needed Capacity

The major components of a water distribution system include pumps, pipes, valves, and storage tanks (or reservoirs). Methods of determining and evaluating existing and required capacity for each type of component are discussed below.

Pumps. Pump capacity criteria are based primarily on water demand. Pumps are sized to provide the maximum day demand in cases where storage is available to meet peak hour, fire, and emergency demands. If storage is not available, the latter three considerations will impact pump sizing.

Designers must consider the full range of possible demands, including minimum as well as average and maximum demands, and select a pump or pumps that will operate within the manufacturer's recommended operating range under the range of anticipated demand conditions. Pump sizing typically starts with maximum day demand conditions (design flow) and pressure design criteria (design head). A pump curve describes the relationship between flow and head for a given pump, and pumps operate at different efficiencies along this curve. A representation of a typical centrifugal pump curve is shown in Figure 2-1.



Courtesy of Ellen Hall, Hazen and Sawyer.

Figure 2-1 Pump and system head curves

Abbreviation: $NPSH_R$, net positive suction head required.

The operating point for a given centrifugal pump in a given system is determined as the point at which the pump curve intersects the system head curve. System head curves are graphical representations of the first law of thermodynamics (Bernoulli equation for water) and are calculated as a function of the elevation (static head) and head loss in the system. System curves can be calculated for different design conditions. For example, the two system curves and resulting operating points shown in Figure 2-1 (points 1a and 1b) might represent operating conditions at high and low tank levels. System curves can also be developed for different demand conditions, different Hazen-Williams coefficients (C-factors), multiple pumps running in parallel, and similar conditions. To properly size a pump, multiple system curves should be developed to represent the full range of operating conditions that the pump or pumps are expected to experience in the system. The most efficient pump selection is one with a curve that crosses the average day system curve (i.e., the curve on which the pump will operate for the majority of the time) at or near its best efficiency point (point 2) and otherwise falls within the envelope of all the system curves.

Continuous operation near the shutoff head of the pump (point 3) or the run-out point (point 4) should be avoided due to low efficiencies, potential for vibration, and, in the case of point 4, potential for insufficient suction head. The required net positive suction head ($NPSH_R$ in Figure 2-1) may exceed the net positive suction head available, causing cavitation. Failure to consider the full range of possible system curves can result in inadequate supply to the system and/or poorly operating pumps. For more information on the pump selection process, refer to Mays (2000), Jones et al. (2008), and the Hydraulic Institute Standards (latest edition).

The desired head is related to system pressure criteria (Table 2-1). Most utilities seek to maintain system pressures between 40 and 150 psi at all times of day. Some utilities aim for an even higher minimum of 50 psi to accommodate items such as taller structures, residential sprinkler systems, or head loss through building backflow preventers (AWWA Manual M35); others may select lower values in order to reduce leakage through pressure control. The higher end of this range (150 psi) is a typical value based on common pressure ratings for pipe (e.g., the thickness classes given in ANSI A21.50 for ductile iron pipe). However, utilities in mountainous terrain may require pipes that have significantly higher pressure ratings. While pump capacity can be largely impacted by system pressures in certain situations, such as a closed pressure zone without elevated storage, pipe size is often the more critical factor for maintaining adequate pressures, as discussed below.

Table 2-1 Typical pipe capacity design criteria

Criteria	Typical Range
Minimum pressure under average day, maximum day, and peak hour conditions	30–50 psi*
Minimum pressure under fire flow conditions	20–30 psi*
Maximum pressure	80–150 psi†
Maximum velocity	5–10 fps*
Maximum head loss under peak hour conditions in pipes smaller than 12 in.	2–3 ft/1,000 ft
Maximum head loss under peak hour conditions in pipes ≥12 in.	1–2 ft/1,000 ft
Required fire flow	500–3,500 gpm‡

* See AWWA Manual M32 (2005).

† Many plumbing codes require pressure-reducing valves (PRVs) on services if pressure is greater than a set value, such as 80 psi. However, distribution system piping may be designed for greater pressures if needed due to topography or other factors.

‡ Gallons per minute varies depending on the type of structure; Insurance Services Office, Inc. ratings; local fire officials' requirements; and similar guidelines. The low end of the range shown represents the typical capacity of a single hydrant; the high end of the range is discussed in AWWA Manual M31 (1998).

Utilities must also size pump stations for the proper firm capacity. Firm capacity is defined as the capacity of the pump station when the largest pump is out of service. For systems with storage, pump stations are typically designed with a firm capacity equal to the maximum day demand. Utilities often design pump stations to ensure that existing and future demand conditions can be met with the installed pumps. However, it is important from both hydraulic and water quality standpoints to not oversize individual pumps for future demand conditions. Multiple smaller pumps are often a better choice, so that they function more efficiently under existing demands. Multiple pumps of different sizes or variable-speed pumps can also be considered in order to accommodate a range of demands. Providing space for future pumps allows flexibility while avoiding excessive installed capacity under existing conditions.

Pump capacity should always be considered in conjunction with pipe and storage capacity. A capacity restriction in any given area could potentially be resolved using a pump upgrade, a pipe improvement, a storage improvement, or a combination of these.

Pipes. The primary design criteria for pipe capacity include velocity and pressure. The goal is to select pipe sizes that are sufficient to prevent excessive head losses (and thus minimize pumping energy required) and, for systems designed to provide fire protection, adequate pressure at needed fire flows. Fire flows impact both pipe and storage sizing and are often the dominant factor in pipe sizing.

Table 2-1 lists some typical ranges of values for pipe design criteria in North America. Design criteria vary widely around the world. While this table presents typical ranges for comparison purposes, individual systems may have circumstances that call for criteria outside these ranges. For example, a need to deliver flow over varying elevations may result in a transmission main being designed for pressures that are much higher than typical pressures in some areas, or the need to provide fire protection to a specific type of industrial customer may result in a higher required fire flow based on the International Organization for Standardization guideline (AWWA 1998). Surge pressures can be substantially higher than normal operating pressures and must also be considered in determining design pressures for pipes. With respect to pipe size and fire flows, 6-in. pipe is the minimum diameter recommended in North America on which to install a hydrant (AWWA 1998).

Determining system pressures in pipes under existing or future conditions can be accomplished in different ways. To investigate an existing pressure issue, pressure gauges are installed in accessible locations such as hydrants and pumping stations. Several options exist for online distribution pressure monitors that can detect low pressures during various demand conditions and over long periods of time. Chapter 9 discusses online pressure monitoring for pressure management in distribution systems in more detail. However, pressure measurements cannot predict pressures in a network under future conditions when demands may be higher, lower, and/or distributed differently than under existing conditions; when operations might be significantly different; or when future facilities may be in place. Hydraulic models can be used for this purpose. They can also help identify higher elevation areas where low-pressure issues are most likely to occur. These higher elevation areas are often the limiting factor in determining the desired hydraulic grade for a given zone within the distribution system.

In order to design new pipes for an existing distribution system, the designer must know the head losses in the existing system. This is done with loss-of-head tests. Head loss measurements are equivalent to the drop in the hydraulic grade line between the inlet and outlet of a test section. Pressure measurements are taken at hydrants, air valves, or other taps. Measurement techniques depend on field conditions and the amount of head loss measured (AWWA 2005). Similar to other pressure measurements, the results are valid only for the flow conditions created for the test. However, results can be used to calculate the roughness coefficient for the particular segment of pipe tested. This information can be used for hydraulic model calibration, and models can be used to examine head loss under future demands and/or operations. The hydraulic model can also be used to identify any current and new pipes above the maximum velocity. Refer to AWWA Manual M32 (2005) for further information on conducting loss-of-head and other types of hydraulic tests, and see *Use of GIS and Hydraulic Models*, later in this chapter, for further discussion on the use of hydraulic models.

Valves. Isolation valves are nominally sized based on pipe diameter and are located based on the need to shut down distribution system segments. Selecting the location, size, and settings of control valves in a distribution system involves detailed analyses.

Control valves include PRVs, pressure-sustaining valves, throttling valves, and check valves. Control valves are often used at pressure zone boundaries. Size, type, and settings are very system specific and depend on the valve's intended purpose. PRVs, for example, are often used in low-elevation areas. Use of PRVs to avoid overpressurization can help reduce water loss; however, this can also lead to higher water age in the PRV zone due to the isolation from surrounding demands. PRVs can also be used for fire protection between zone boundaries where the boundary needs to remain closed unless a certain low pressure is reached during a fire flow condition. The pressure setting allows the valve to fully open, providing flow across the zone boundary as needed during a fire.

Valve sizing is outlined in AWWA Manual M44 (2015b). However, valve settings and controls should be set with both pressure criteria and water quality goals in mind. For example, allowing more flow through PRVs by having a small bypass line (approximately 1-in. diameter) open at zone boundaries can relieve both sides of potential dead ends and improve water age (Cruikshank 2010).

Storage. The design of new storage or the evaluation of existing storage is dependent on two basic factors: volume and hydraulic grade. Storage volume is typically determined using either standards-driven or functional methods (Mays 2000). Standards-driven methods are often general requirements for total storage in which a total storage volume that equals some percentage of average or maximum day demand is required. One-half the average day demand or an equivalent definition based on gallons per connection is

an approach used in several US states. This approach tends to produce more conservative results than a functional approach (AWWA 1998; Ten States Standards 2012).

The functional method considers the following three categories of storage:

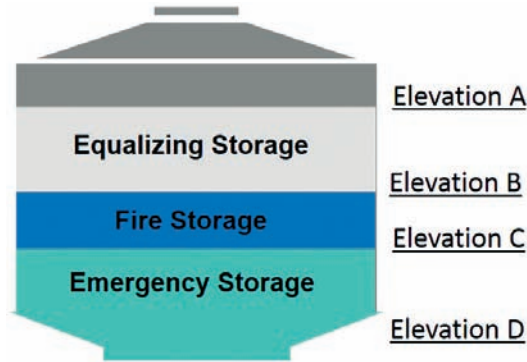
- *Equalizing storage* provides water when the demand exceeds the rate of supply. Providing flow equalization from storage allows water production facilities to be sized for maximum day (rather than peak hour) demand and allows them to operate at a relatively constant rate, which is advantageous for process control. Equalizing storage is most commonly expressed as a percentage of the maximum day demand. Typical values range from 10 percent to 25 percent of the maximum day demand. Larger systems or pressure zones tend to be at the lower end of this range, while smaller systems tend to be at the higher end due to the demand averaging effect that occurs in larger systems.
- *Fire storage* is the volume of water required for fire fighting, usually expressed as a fire flow multiplied by a fire duration (e.g., 3,500 gpm for 3 hours [AWWA 1998]). The utility determines the fire flow and duration based on building codes, input from local fire officials, the desire to maintain the community's insurance rating from the Insurance Services Office, or other criteria. The flow and duration can vary significantly depending on land use (residential, commercial, institutional, or industrial), building construction materials, and spacing of structures. AWWA Manual M31 (1998) outlines many of the recommended practices.
- *Emergency storage* is the storage volume required to maintain service during an emergency, such as loss of a supply or a main break. Emergency storage requirements vary from utility to utility and are typically based on an assessment of the level of reliability and redundancy present in the system, the typical frequency and duration of emergencies, and other factors. For example, if a system has more than one source and has standby power, there is less need for emergency storage, whereas with a single source and no standby power, more emergency storage may be warranted. Values are typically expressed as a percentage of demand or time at the average day demand or maximum day demand (e.g., 25 percent of the average day demand or 4 hours of supply at the maximum day demand).

Along with the functional categories, storage may also be categorized as effective or ineffective as follows:

- *Effective storage*, also known as usable storage, is the volume of stored water at or above the level at which the minimum pressure is attained (in tanks that float on the system) or above which the water can be pumped (in pumped storage).
- *Ineffective storage*, also referred to as nonusable storage or dead storage, is the volume of stored water below the level at which the minimum pressure is attained (in tanks that float on the system) or below which the water cannot be pumped (e.g., due to suction head limitations in pumped storage).

Figure 2-2 is a conceptual schematic of these storage volumes and elevations, representing the boundaries of effective storage for each category. Methods for determining the volumes and elevations (or hydraulic grades) for each category are discussed below.

Determining the equalizing storage volume. To determine the needed equalizing storage volume, diurnal demand patterns can be calculated using measurements of flow and storage tank volume changes and/or historical production, pumping, and tank level records (Bates et al. 1996). An example calculation is shown in Table 2-2 for a system with one water treatment plant (assuming no purchased water supplies) and two storage tanks using hourly data.



Courtesy of Meg Roberts, Hazen and Sawyer.

Figure 2-2 Distribution system storage volume design concept

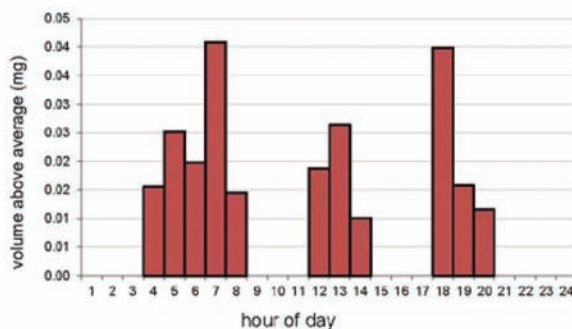
Table 2-2 Example diurnal pattern and equalizing storage volume calculation

Time of Day		WTP Supply (mgd)	Tank 1 Level (feet)	Tank 2 Level (feet)	Tank 1 Flow* (mgd)	Tank 2 Flow* (mgd)	System Demand (mgd)	Fraction of Average	Volume Over Average (million gal)
0	-	1	1.99	21.1	26.2	-0.2	0.5	2.23	1.04
1	-	2	1.00	22.1	24.3	-0.2	-0.5	0.34	0.16
2	-	3	1.01	22.8	26.2	-0.4	-0.3	0.28	0.13
3	-	4	2.35	24.3	27.6	-0.2	0.3	2.51	1.17
4	-	5	1.99	25.0	26.2	0.3	0.5	2.74	1.28
5	-	6	2.00	23.9	24.4	0.5	0.1	2.61	1.22
6	-	7	2.37	21.9	23.9	0.5	0.3	3.12	1.46
7	-	8	2.36	20.1	22.7	0.1	0.0	2.48	1.16
8	-	9	2.35	19.6	22.7	-0.1	-0.2	2.06	0.96
9	-	10	2.49	20.1	23.4	-0.2	-0.5	1.80	0.84
10	-	11	2.49	20.9	25.4	0.0	-0.6	1.87	0.87
11	-	12	2.47	21.0	27.7	-0.2	0.3	2.59	1.21
12	-	13	2.49	21.7	26.6	0.0	0.3	2.77	1.30
13	-	14	2.35	21.9	25.3	-0.1	0.1	2.38	1.11
14	-	15	2.01	22.1	25.0	0.0	0.2	2.27	1.06
15	-	16	2.10	21.9	24.1	0.1	-0.6	1.63	0.76
16	-	17	2.19	21.5	26.4	0.2	-0.4	2.00	0.94
17	-	18	2.36	20.9	27.8	0.0	0.7	3.09	1.45
18	-	19	2.35	20.8	25.0	0.2	0.0	2.52	1.18
19	-	20	2.36	20.1	25.0	0.2	-0.2	2.42	1.13
20	-	21	2.05	19.1	25.7	0.0	-0.3	1.81	0.85
21	-	22	2.02	19.1	26.7	-0.3	-0.1	1.64	0.77
22	-	23	2.01	20.1	27.2	-0.4	0.3	1.96	0.92
23	-	24	2.02	21.7	25.8	0.1	0.1	2.18	1.02
0	-	1		21.4	25.5				

Average (mgd): 2.14 Sum (mgd): 0.2

Equalizing Storage =

$$\frac{0.2}{2.14} = 11\%$$



*assuming cross sectional area of each tank is 1400 square feet

For sizing new tanks, different operational strategies might be considered in order to determine the amount of equalizing storage required. For example, a utility may want to reduce energy costs by shifting booster pumping operations to times of the day when power costs are lower. For a pressure zone supplied by a booster pump within this system, a calculation similar to the one in Table 2-2 could be performed to determine the equalizing storage needed to accommodate the energy-conserving pumping strategy. Enough volume in the tank would be required to supply demand when the booster pumps are off. The water age impacts of this storage volume should be considered in evaluating the energy conservation strategy.

The hydraulic grade of equalizing storage in a tank depends on whether or not the tank is equipped with a pump station to pump water out of the tank into the distribution system. Most elevated storage tanks are not equipped with this; therefore, the entire equalizing storage volume is only effective if it is located above a hydraulic grade that provides adequate pressure to all customers served by the tank at all times of day (elevations between A and B in Figure 2-2). Whether or not pressure is adequate depends on the distribution system's pressure criteria. As discussed above, many utilities have a lower daily pressure requirement of between 30 and 50 psi. However, this design criterion can vary significantly, even within a single distribution system, depending on specific customer needs.

Determining fire storage volume. Fire storage volume requirements are often calculated by multiplying the maximum fire flow demand by the required duration. However, some utilities do not include a fire storage volume in their storage volume criteria. Instead, they supply the required fire flow and duration using other system capacity, such as fire pumps, additional treatment plant capacity, and/or interconnections with other systems. Hydraulic models can be used to test the effectiveness of storage or other methods in providing the required fire flow and duration at various locations in the system.

For most distribution systems, the minimum required pressure for fighting fires is 20 psi. At this pressure, fire pumper trucks can adequately supply water and contamination from vacuum pressures in the piping network is prevented (AWWA 1998). If the bottom of the fire storage volume (elevation C in Figure 2-2) is not at a hydraulic grade to provide 20 psi, the volume is ineffective. Fire pumps would be required to meet fire storage design criteria. Other systems may require a higher distribution system pressure for fighting fires. Some facilities are equipped with their own fire pumps that require a higher suction side pressure. If these facilities are critical (e.g., hospitals), the utility may have higher pressure criteria at certain locations.

Determining emergency storage volume. Different utilities or regulatory agencies have differing requirements for emergency storage volume. Some do not require any emergency storage volume, as they may have adequate volume at adequate pressure from emergency interconnections with other systems. Others require enough to supply as much as one to two days of average demand. Some utilities require an emergency volume in addition to equalizing and fire storage. Others assume that a fire and emergency condition would not occur simultaneously and so either include only a fire volume or include the larger of the fire or emergency volume.

The required hydraulic grade for this volume (elevation D in Figure 2-2), such as equalizing and fire volumes, varies depending on the topography of the area served, the pressure design criteria, and the ability to pump out of the storage tank. For example, many utilities have clear wells at water treatment plants in order to attain sufficient disinfectant contact time. Utilities may choose to consider their clear well volume as water available during an emergency if generators are available to pump the volume into the distribution system during a power outage. Acceptable system pressures during

an emergency generally vary from 0 to 20 psi. However, some utilities with sensitive or critical facilities require higher pressures under emergency conditions to ensure these facilities remain functional.

Summary. The goal in sizing storage tanks is to store the minimum volume that will meet a utility's capacity needs and to make that volume effective. For example, standpipes with a great deal of ineffective storage add to water age and typically provide only limited capacity for equalizing or fire storage. Excess storage in the distribution system can contribute significantly to higher water age (Snyder et al. 2002).

DETERMINING WATER AGE

The spatial and temporal variation of water quality in a distribution system reflects very complex phenomena, including hydraulic mixing patterns and biological and chemical water quality transformations that can occur within a piping network. Age is a water quality parameter that can serve as a general indicator of water quality conditions that result from this complex set of interactions.

There are several ways to determine water age:

- Hydraulic modeling,
- Tracer studies, and
- Estimate from measured hydraulic and/or water quality data.

Before concerns about water age are addressed, it must first be understood that where treatment processes and source quality are excellent, it is still possible that very old water will have good quality. Conversely, less than optimal treatment and/or a challenging water source with respect to quality can result in faster water quality degradation at lower water age. The distribution system is the third step in water quality optimization; source water and treatment are first and second, respectively.

Hydraulic Modeling

Changes in the age of water throughout a distribution system can be simulated with hydraulic models or indirectly measured using tracer studies (AWWA 2005). New water that enters the network from treatment plants or supplies has an age of zero. Age is treated as a reactive constituent whose growth follows zero-order kinetics with a rate constant equal to 1 (meaning each second the water becomes 1 second older).

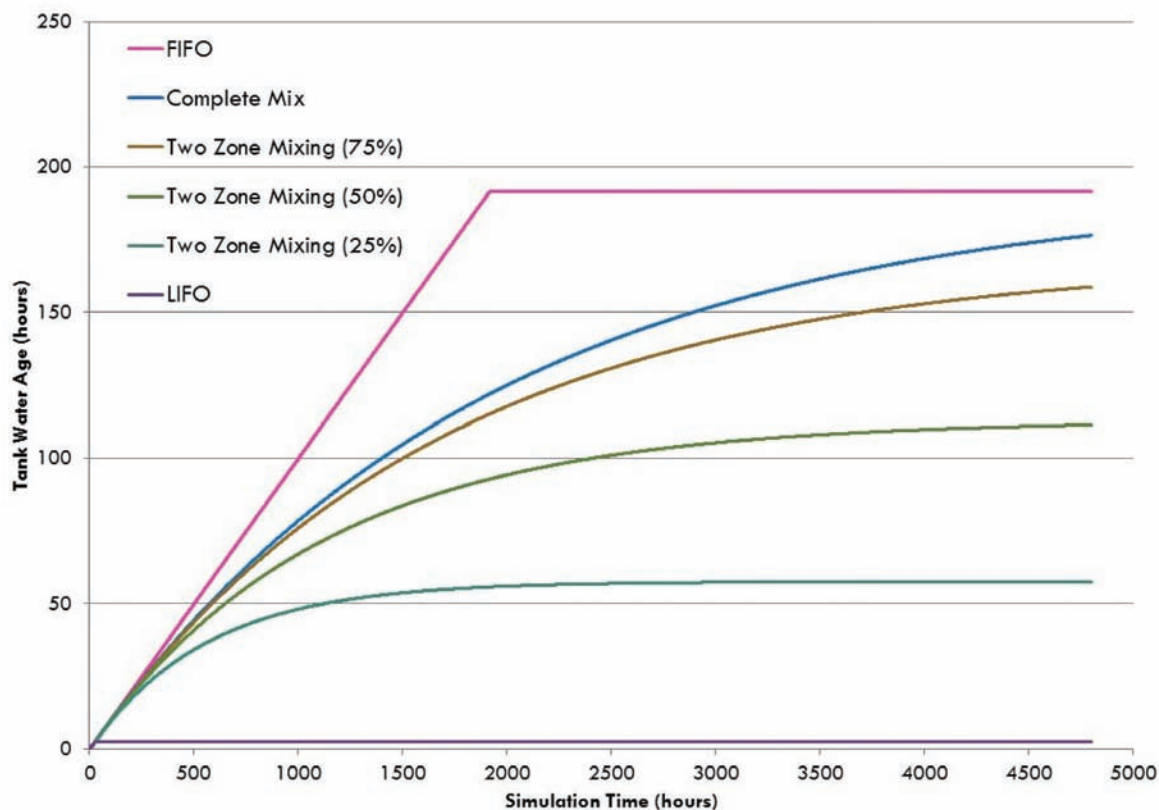
Mathematical determination of water age with a hydraulic model or tracer studies is based on conservation of constituent mass. Advective transport of mass within pipes is assumed (i.e., the constituent mass moves with the bulk liquid), and longitudinal dispersion is not typically considered an important transport mechanism under most operating conditions. This means that there is an assumption of no intermixing of mass between adjacent parcels of water traveling through a pipe.

Distribution system water quality models represent water transport within pipes, mixing at junctions and storage tanks, and appropriate reaction kinetics (zero-order for water age) with a set of mathematical equations. These equations are solved according to an appropriate set of boundary and initial conditions in order to predict the variation of water age through the distribution system (AWWA 2005).

The advantage of using hydraulic models to estimate water age is that the age calculation is purely hydraulic. If a model is calibrated and extended-period simulations are used, water age can be readily predicted at any location in the distribution system under both existing and alternative operating and/or demand conditions. Extended-period

simulations are multiple days in length; water age simulations are run for long periods of time in order to reach a stable, long-term water age in the tanks. Note that the exact length varies for each system and must be determined iteratively using plots similar to those shown in Figure 2-3. Water age is highly dependent on water demand in the network as well as piping configuration and storage tanks. Changes to those inputs can aid in the prediction of improvements to or deterioration of water quality.

The mixing of mass within storage tanks can be simulated by most models using the following four types of mixing regimes: complete mixing, plug flow (first in/first out, or FIFO), short-circuiting (last in/first out, or LIFO), or compartment (two zone). Figure 2-3 shows an example of how the four types of assumed mixing affect water age within storage tanks. In reality, specific storage tank configurations often result in mixing characteristics that are not fully captured by any one of these model representations. Computational fluid dynamics models can be used to represent mixing characteristics of specific storage tanks more effectively. However, for purposes of using hydraulic models to estimate water age, selection of one or more of the available mixing options serves as a basis for comparing possible improvements. Different mixing options are tested in the model in order to determine the sensitivity of the water age results in the choice of mixing regime. Paired temperature or chlorine residual measurements taken at different depths within an existing tank provide an indication of the type of mixing regime present. Calculating the Reynolds number for the flow entering and/or exiting the tank provides an indication of the flow regime (laminar, transitional, or turbulent) at the tank entrance, which indicates how well mixed a tank might be based on its inlet and/or outlet configuration.



Courtesy of Meg Roberts, Hazen and Sawyer.

Figure 2-3 Example of how storage tank mixing characteristics affect tank water age effluent

Using hydraulic models to determine water age, however, does have drawbacks. Models are fairly input intensive and, in addition to software costs, time and information are required to build, calibrate, and effectively use them. Many utilities, especially smaller systems, do not have sufficient staff to create and maintain a model in-house. While calibration can improve the assumptions used, models do require a certain number of assumptions and have limitations in accuracy (hydraulic grade lines within 5 ft and flows within 10 percent are good goals for calibration [AWWA 2005]). If a model is not available, the residence time contributions from the tanks in a system can be calculated and trended over time using supervisory control and data acquisition data (e.g., tank level, FIFO, tank dimensions), with FIFO inferred from change in the tank level over time.

The important thing to consider with these mixing regimes is that the LIFO and zone mixing regimes shown in Figure 2-3 have water age that is lower than the other regimes at the outlet of the tank, but this is due to short-circuiting. This means that the water age and water quality at higher levels in the tank can be significantly worse and may be detrimental to water quality in the distribution system at times when that water is released (higher demands or operations that draw the tank levels down more than usual).

To address this issue and achieve more uniform water quality in tanks, many utilities use active or passive mixers in an effort to achieve a mixing regime that is closer to the complete mix regime. To be effectively sized and placed, such mixers need to be evaluated based on the geometry and inlet/outlet configuration of the particular tank before installation.

Tracer Studies

Tracer studies are another method for estimating water age. A tracer is a conservative compound, that is, it does not grow or decay. Conducting a tracer study to determine water age involves injecting a tracer at the entry point to the distribution system, shutting off or reducing a continuous chemical feed at the entry points, or using a substance that occurs naturally in the source water. The concentration of the tracer is measured over time at various places in the distribution system, and the tracer data is used to calibrate the water quality model. A tracer study requires careful planning and implementation but may still be a more economical alternative for some utilities compared to developing a hydraulic model (Clark 2012). However, the results of a tracer study reflect only the specific locations sampled and the operating conditions at the time of the study. They cannot be used to predict water age under future conditions or for what-if scenarios.

Estimating from Hydraulic and Water Quality Data

Real-time monitoring of constituents such as disinfectant residual or a naturally occurring tracer provides results similar to those gained from a tracer study but over a longer period of time. Average age in a particular storage tank can also be estimated directly from operating data (water level and tank geometry), and paired measurements of disinfectant residual at different depths within a tank can provide an indicator of stratification within the tank. Improvements in automated monitoring equipment continue to be made, and software tools to integrate real-time data with hydraulic models are becoming available and will continue to evolve. As these tools are developed, they will become more reliable and accessible to more utilities and will help to provide a better understanding of existing system conditions over time.

Summary

It is important to note, however, that each distribution system is a unique biological and chemical reactor with different source waters, treatment processes, and facilities. As such, the absolute value of water age has limitations as a water quality indicator. Water quality data should be assessed in conjunction with water age to determine age values that are appropriate for each system. However, what-if scenarios that involve predicted water age are useful for the purpose of evaluating potential changes in system configuration and/or operations.

Characterizing the DSWQ Challenge:

Determine Needed Capacity

- Pumps: demand and pressure conditions
- Pipes: pressure, velocity, and head loss
- Valves: sizing and hydraulic functionality
- Storage: storage volume criteria for equalizing, fire, and emergency storage

Determine Water Age

- Hydraulic modeling
 - Tracer studies
 - Estimate from measured hydraulic and/or water quality data
-

WAYS TO BALANCE CAPACITY AND WATER AGE

Every water distribution system has many of the same basic components: pipes, pumps, valves, storage facilities, and so forth. However, the particular combination of source water quality, geography, and infrastructure in any given system makes it unique, and finding solutions to any water quality issue requires careful examination of all the factors involved. Water age can be a surrogate for a number of different parameters and can be determined using a calibrated hydraulic model or tracer study or be estimated from measured hydraulic and/or water quality data. Consequently, water age is a good place to start when analyzing a water quality issue. This section describes ways in which capacity criteria and operational practices can be modified to better balance capacity and water age.

Water Age Considerations for Capacity

The design criteria selected for use in sizing distribution system components can have a significant impact on water age. Some criteria are related to the essential function of the distribution system—to deliver water at sufficient flow rates and pressures; any significant deviation from these criteria would have the potential to compromise the system's basic functionality. However, there are areas of criteria selection and application that can be more individualized to a particular system, giving more flexibility to consider water quality impacts when selecting the criteria. Storage volume criteria, in particular, fall into this latter category and are discussed in detail later in this section.

Pipes. A consequence of sizing pipes to provide fire flows is higher water age under normal demand conditions (Snyder et al. 2002), especially for dead-end mains with limited demand. While fire flow criteria may be predetermined and some dead ends are inevitable due to topography, land use limitations, and cost, utilities can evaluate solutions such as looping pipes and providing small-diameter bypasses on zone boundary valves in order to eliminate dead ends with water age issues. For cases in which a branched rather than looped design is necessary or preferred, utilities may consider flushing to improve water age (see Flushing Programs later in this chapter). When analyzing alternatives, it is beneficial to consider the trade-offs between increased fire flow and reliability and the potential for water quality degradation in a looped system as compared with a branched system (see Chapter 5 for more discussion of branched and grid/loop designs).

When planning for future demands, installation of very large transmission mains can add a significant amount of water age and degrade water quality, especially in the early years of development before an area is built out. Phased parallel piping may be preferable. Although higher in cost, the near-term improvement in water quality is often favorable, and, in the long term, parallel pipes provide added redundancy. Alternatively, phasing capital improvement projects by demand triggers instead of planning years can help reduce overcapacity issues. Demand forecasts, while helpful for capital improvement planning, are often based on population projections that vary over time and are based on assumptions that may change. For major hydraulic upgrades that are required to meet future demand scenarios, tracking water demand in specific areas of the system is useful as a trigger to schedule construction on large transmission mains. In this way, the full capacity that is needed in the future does not cause water age problems in the present. For example, a utility may track demand by district or pressure zone and initiate a new pipe project when demand in that district or zone reaches 80 percent of the demand at which the pipe is needed. Water age modeling may be used to assess the impacts of pipe improvements under different demand conditions, and the results may be used to aid in the phasing of capital improvements.

Pumps. Sizing multiple pumps so that there is continuous pumping from a pump station helps to minimize water age by preventing stagnant water in transmission mains. The energy costs of different sizing options and operational strategies should be considered when evaluating pumping alternatives. Energy costs can vary significantly depending on the rate structure in effect for a particular facility. Utilities need to balance water age improvement with energy costs or find opportunities to improve both. Similar to pipeline capital improvement projects, pumps are upsized based on demand triggers in lieu of planning years.

Storage. There is an increasing awareness that the standards-driven storage volume criteria of the past do not adequately address the potential water quality impacts of this quantity of storage. Excessive storage should be avoided (Kennedy et al. 1993). An updated approach to storage volume criteria is to focus more on effective rather than total storage and consider functional criteria such as equalizing, provision of fire flows, and emergency supply and system reliability. Hydraulic modeling can be used to check the true functionality of the criteria selected, consider the interconnectedness of systems, and assess system reliability under different scenarios such as fires, major pipe breaks, and use of alternate sources.

Of the three functional categories, equalizing storage is the most basic hydraulic requirement. If the supply is designed for the maximum day demand, equalizing storage must be provided to handle peak demands in excess of the daily average. Fire and

emergency storage can be more flexible in terms of the criteria that a utility selects and the ways in which the utility applies the criteria. For example, the fire volume of a given tank could potentially be shared with a lower pressure zone if sufficient pipe capacity exists and the second zone is at the same or lower hydraulic grade or if reliable pumping is provided (AWWA 1998). This type of option can be tested using a hydraulic model or field measurements to determine whether required fire flows can be met in both zones. Water age rises sharply in cases where fire and emergency storage exceed 80 percent of the total storage volume (Snyder et al. 2002), so fire and emergency storage criteria are key places to look in evaluating (or reevaluating) storage capacity.

Ineffective storage has limited usefulness and is one of the largest contributors to increased water age. While ineffective storage can serve a structural function of supporting the water above it, it has the negative impacts of increased water age and stratification within a tank. One way to help meet capacity needs while minimizing water age is to minimize ineffective storage in the system. One method of doing this is to choose elevated tanks rather than standpipes for floating storage. Standpipes have a greater amount of ineffective storage than other tank types. Also, stratification is more likely to occur in them, and it is harder to break up the stratification with the inflow jet entering the tank (Grayman et al. 2000). A ground storage tank with an operating range comparable to that of an elevated tank may also be a good option for floating storage if a site with a sufficiently high ground elevation is available. For pumped storage, the ground storage tank should be designed such that the pumps can draw a large fraction of the tank's volume.

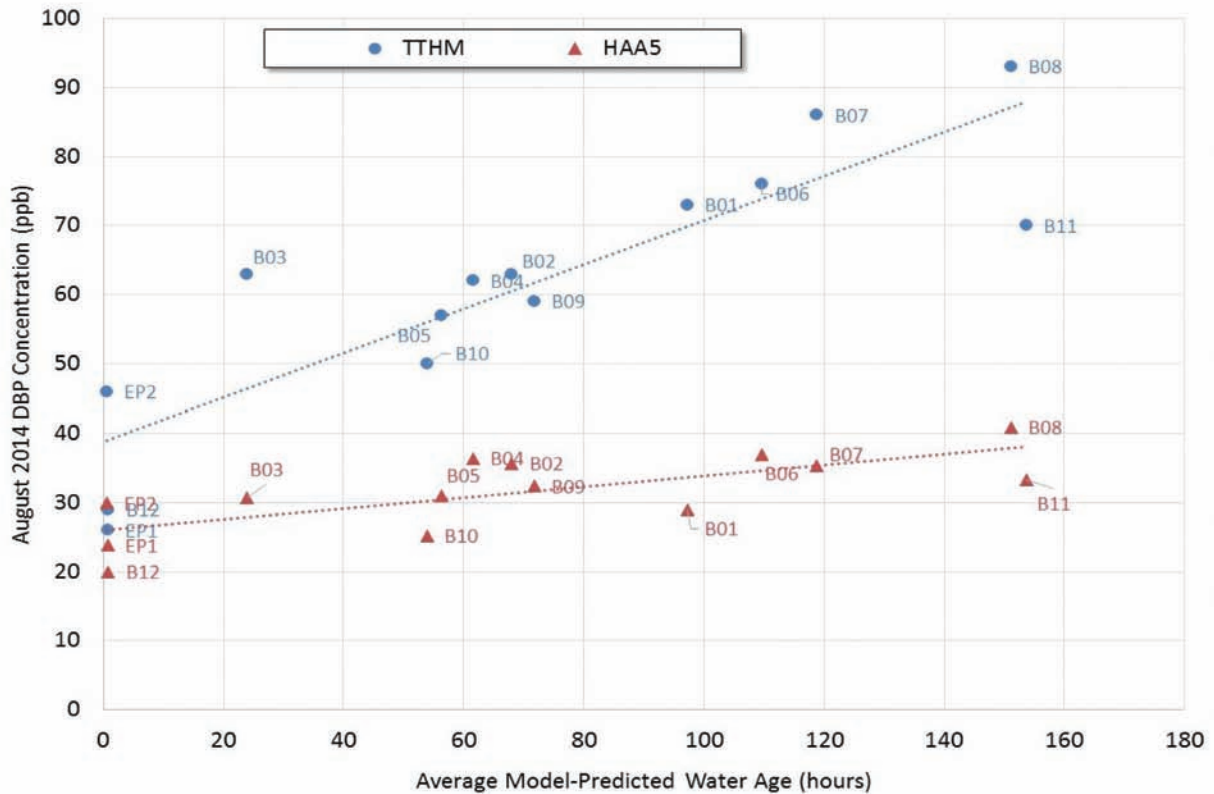
Designing storage tanks for conditions that rarely, if ever, occur is a challenge for many utilities. This is especially true for systems with wide seasonal fluctuations in demand; sizing storage for the maximum day demand results in long residence times in the off-season. It may be possible to take some storage off line during low-demand periods. Utilities also look for opportunities to develop emergency interconnections or other redundancy plans that would provide emergency supply in lieu of excessive emergency storage.

Water age criteria. Water age goals should be determined by examining existing water quality measurements and comparing them to water age. A statistical analysis of chlorine residual at locations with known water age, for example, can help set a water age goal. Quarterly DBP correlations are another option.

Figure 2-4 shows an example of a system that uses free chlorine with a water age goal of five days to minimize total trihalomethanes based on historical data review and predicted water age calculations from a calibrated hydraulic model. In systems where temperature fluctuations are high, seasonal trends should be evaluated with different water age goals.

Water age design criteria are very system specific, and there is no ideal water age for all systems (Friedman et al. 2010). The extent to which water age impacts water quality depends on numerous factors, including source water quality, treatment process efficiency, the water's microbial and chemical stability, disinfectant type and dose, and distribution system configuration, condition, and operation (Friedman et al. 2010). However, water age can be estimated within a given system and the results used to help guide design and operational decisions.

Simulated distribution system testing can estimate a bulk disinfectant decay curve or DBP formation curve to predict and manage disinfectant and DBP levels based on estimated water age in the distribution system. (see Figure 2-5 for an example and refer to *Standards Methods for the Examination of Water and Wastewater*, 22nd ed., for procedure). Measuring decay or formation due to pipe wall interactions is more complex, and a standard



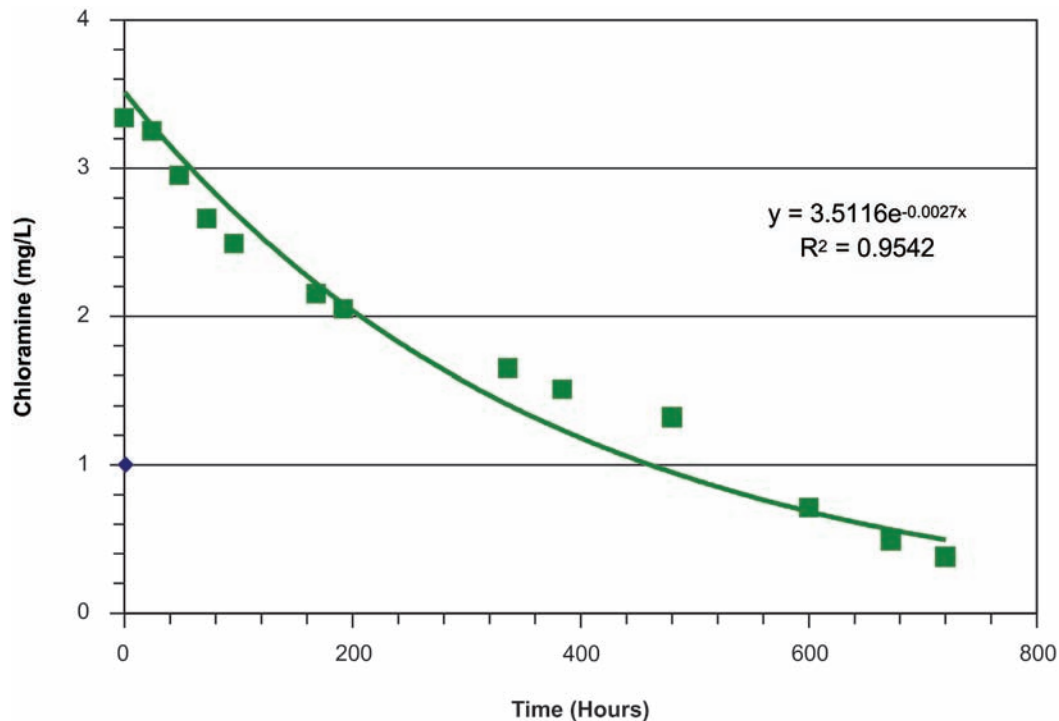
Courtesy of Meg Roberts, Hazen and Sawyer.

Figure 2-4 Increasing disinfection by-products with water age in a free-chlorinated system

procedure has yet to be developed. Even between constituents within a single water, there is no ideal age; however, measuring several parameters will give an idea of the most desirable range (Cruikshank 2010). Alternatives designed to bring the system within the desired range can then be developed. If modeling or other studies indicate that this range is not practically attainable with changes to distribution system capacity or operations alone, changes in treatment may be needed (Kirmeyer et al. 2000). For more information on disinfection and disinfectants, refer to Chapter 8.

Operations

Capacity and water age depend not only on the physical characteristics of a system but also on how the system is operated. Many operational changes reduce water age at relatively little cost, making operations a good place to start in identifying solutions to capacity and water age issues.



Courtesy of Jeff Cruickshank, Hazen and Sawyer.

Figure 2-5 Example of chloramine bulk decay curve

Pipes. Adjustments to piping configurations to improve water age may be made operationally by changing valve positions or settings. Examples of changes that can be made to improve water age include the following:

- Allow flow through zone boundary valves: Closed valves at pressure zone boundaries often function as dead ends in a distribution system. Allowing these valves to bleed back a small amount of flow from a higher pressure zone to a lower pressure zone by opening a bypass around a gate valve, throttling a valve, or changing the opening setting of a PRV can improve water age in the area of the valve without consuming any water (Cruikshank 2010). Care should be taken when throttling valves to ensure integrity is not compromised.
- Reconfigure tank connections: The configuration of the piping entering and leaving a tank can have a significant impact on water age in the tank (Grayman et al. 2000). A tank configured with a separate inlet and outlet and control valves to prevent reverse flow can help improve the flow pattern, provide some mixing, and reduce stratification in the tank. Keeping bypass piping closed also helps to maintain a higher rate of flow into the tank. This allows a higher velocity from the inflowing jet, which improves mixing.
- Close valves to change flow patterns: One way to improve circulation through an area with high water age is to strategically close valves to increase velocity through the area (Cruikshank 2010) and possibly route the water to areas with higher consumption within the system. Closure options should be tested using a hydraulic model or water quality sampling to ensure that new areas of high water age near the closed valves will not be an issue. An increase in velocity could cause

a release of accumulated sediments. Flushing to remove sediment prior to the change can help provide a controlled release and removal of accumulated sediments (see Appendix B for more information on flushing).

- Encourage water use at system extremities: The utility can consider encouraging large water users at extremities of the piping network to use more water (e.g., irrigation of golf courses or athletic fields, industrial uses) through education or rate incentives. Additionally, spot flushing can reduce water age at selected locations (see Flushing Programs later in the chapter).
- Consider the effect of multiple supply sources: If there is a choice between multiple supply locations, the supply to use can be chosen in order to minimize water age in the distribution network of pipes. For example, two sources on opposite sides of a distribution system tend to produce lower water age results than two sources that are close together, as both sides have initial water ages of zero at each entry point (Cruikshank 2010). This should also be a consideration in evaluating future supply alternatives. The quality of the source water and treated water from each supply should also be taken into consideration, depending on the system's water quality challenges.

Pumps. The way that pumps are operated can have a significant impact on water age. Some examples of how pump operation can be modified to improve water age include the following:

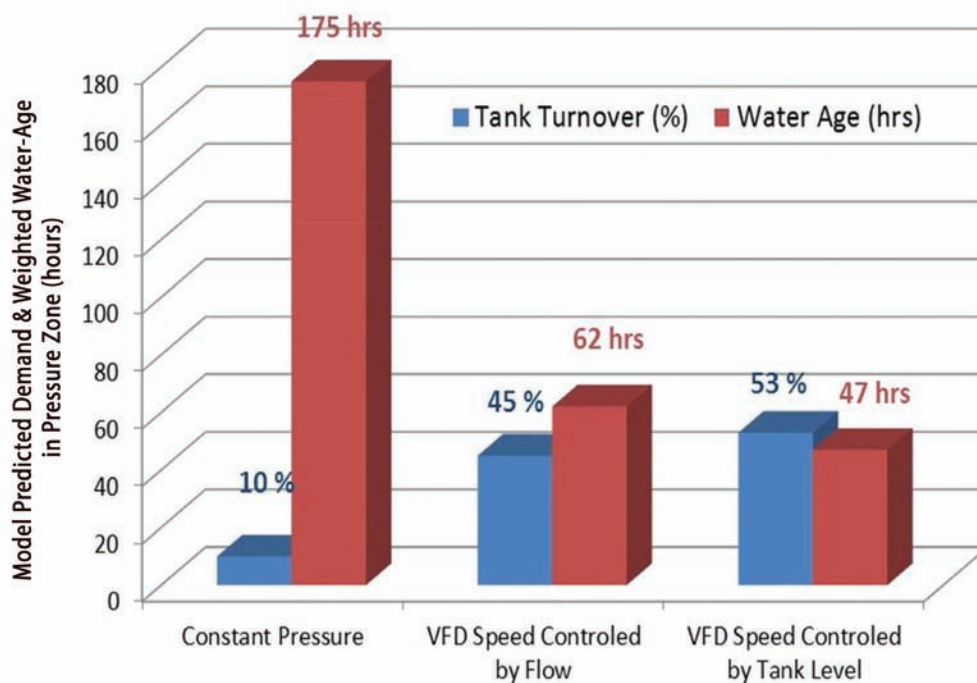
- Change pump settings to improve tank turnover: Adjust pump on and off settings to produce the maximum amount of volumetric turnover allowable without compromising pressure or fire flow design criteria.
- Pump across zone boundaries: Pumping at multiple locations along a zone boundary rather than pumping at one boundary and using only PRVs at other boundaries is another method for eliminating dead ends at zone boundaries.
- Control variable-speed pumps advantageously: Many variable-speed pumps are controlled based on maintaining a pressure setting. This produces consistent system pressures but can result in low turnover in tanks. Controlling variable-speed pumps based on a flow setting can improve tank turnover by allowing the pumps to shut off and the tank to draw (Cruikshank 2010). Variable-speed pumps can also be controlled based on tank level, which can improve water age even (Figure 2-6). In this case, running the pump at a high speed when the tank drops to a certain level and at a low speed as it approaches full can produce optimal results.

Storage. Areas of high water age are often centered around storage tanks. Following are some operational strategies for improving water age in tanks:

- Reduce storage volume: Use less volume within an existing tank by adjusting both pump-on and pump-off settings. Do this to the extent feasible without compromising pressure or fire flow design criteria (Cruikshank 2010).
- Increase turnover: Use a larger fraction of the volume in a tank during regular operations by balancing pump settings and customer draw down (Cruikshank 2010).
- Use mixing strategies to improve flow patterns and produce a consistent water age: While mixing cannot reduce the average water age within a tank, it can help provide homogeneity and prevent stratification and zones of high water age from forming within the tank.

- Take a tank off line seasonally or permanently: If a tank with high water age causes seasonal issues, consider temporarily removing the tank from service during the period when the issues typically occur. If the tank volume exceeds capacity requirements or represents emergency storage that could be provided in other ways, a utility should consider taking the tank off line permanently. The pressure and fire flow impacts should be evaluated before implementing either alternative, and the tank should be drained and cleaned before placing it back into service.
- Direct bulk water haulers to draw water from high-age tanks: A hydrant near a tank can be designated for this purpose to increase tank turnover.
- Use ground storage with pumps and and/or control valves to circulate water: Many distribution systems have ground storage tanks, the hydraulic grade of which requires pumps to draw down water and/or control valves for filling. Turning over the tank volume on a regular basis with valve and pump controls can help circulate water in the distribution system and reduce aging inside the ground storage tank.

Summary. There are only two ways to truly achieve a net reduction in water age in a system—increase demand (e.g., by flushing) or reduce the volume of water stored in the system. Other operations such as tank mixing do not cause a net reduction in water age but rather make the age more uniform. Unless demand is increased or storage is reduced, when localized reduction in water age is created in one place, a commensurate increase is occurring somewhere else (though potentially spread over a larger area). The goal is to ensure that changes do not inadvertently create additional high water age areas. Such areas can occur at locations completely removed from the initial area of concern, which is one reason why hydraulic models of the complete system are useful in evaluating water age reduction alternatives.



Courtesy of Jeff Cruickshank, Hazen and Sawyer.

Figure 2-6 Example improvements in water age by controlling pump speed by flow or tank level

Maintenance Programs

While every distribution system requires some reactive maintenance, proactive maintenance programs or asset management programs can function to reduce reactive maintenance needs, manage costs, and, in general, produce a better functioning system.

Pipes. Pipe condition and maintenance impact many aspects of distribution system water quality, including chemical and microbial interactions with the pipe as well as capacity and water age issues.

Tuberculation or other deposits on the interior pipe wall can result in greatly reduced capacity. For example, Figure 2-7 shows a sample from a pipe that was determined to have significant head loss, as reflected by a C-factor of 22. The head loss in this pipe could create a capacity problem, particularly for fire flows, and also exacerbate water age-related issues such as increased microbial activity (see Chapter 3 for more information on managing the microbial community). Utilities can use fire flow capacity needs and water age as criteria when prioritizing a capital improvement program. For example, a flow path to move water directly to an area with high water age or low fire flow may be created by rehabilitating or replacing certain sections of pipe first. Refer to Chapter 4 for more information on aging infrastructure and pipe rehabilitation and replacement programs.

Valves. Valves are an often overlooked system component that, if not maintained, can lead to an increased risk of property damage and service disruption during main breaks, as well as hydraulic restrictions that diminish the quality of service. There are two basic components to a valve maintenance program (Bloetscher 2011):

- Locating and accessing the valves, and
- Operating the valves on a regular schedule (annually is a good goal). Any valves that are found to be not operational should be repaired or replaced.

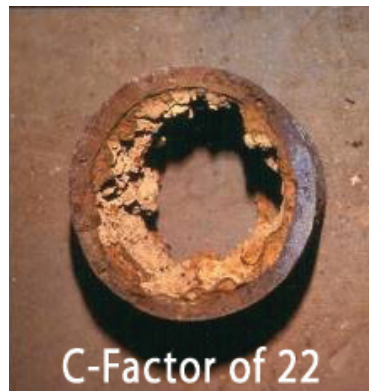


Figure 2-7 Tuberculated pipe with reduced capacity

Additionally, all utilities find valves that are closed but should be open. More closed valves can be identified if all valves are located and operated on a regular basis. Closed valves create hydraulic constrictions that can impede fire flows and reduce hydraulic capacity in an area. Areas isolated by closed valves can also exhibit increased water age (and deteriorated water quality) due to the lack of flow. Depending on their location, closed valves have the potential to impact water age and quality in large areas of the distribution system.