GUIDANCE ON MONITORING THE

BIOLOGICAL STABILITY OF DRINKING WATER IN DISTRIBUTION SYSTEMS

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Conseils sur la surveillance de la stabilité biologique de l'eau potable dans les réseaux de distribution

To obtain additional information, please contact:

Health Canada
Address Locator 0900C2
Ottawa, ON K1A 0K9
Tel.: 613-957-2991
Toll free: 1-866-225-0709
Fax: 613-941-5366
TTY: 1-800-465-7735
E-mail: publications-publications@hc-sc.gc.ca

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TABLE OF CONTENTS

BACKGROUND **ON GUIDANCE DOCUMENTS**

Health Canada works with the provinces, territories and federal agencies to establish the Guidelines for Canadian Drinking Water Quality. Over the years, new methodologies and approaches have led Health Canada, in collaboration with the Federal-Provincial-Territorial Committee on Drinking Water, to develop a new type of document, guidance documents, to provide advice and guidance on issues related to drinking water quality for parameters that do not require a formal Guideline for Canadian Drinking Water Quality.

Guidance documents are developed to provide operational or management guidance related to specific drinking water–related issues (e.g., boil water advisories), to make health risk assessment information available when a guideline is not deemed necessary.

Guidelines are established under the Guidelines for Canadian Drinking Water Quality specifically for contaminants that meet all of the following criteria:

1. exposure to the contaminant could lead to adverse health effects;
2. the contaminant is frequently detected or could be expected to be found in a large number of drinking water supplies throughout Canada; and
3. the contaminant is detected, or could be expected to be detected, at a level that is of possible health significance.

If a contaminant of interest does not meet all these criteria, Health Canada, in collaboration with the Federal-Provincial Territorial Committee on Drinking Water, may choose not to develop a Guideline Technical Document. In that case, a guidance document may be developed.

Guidance documents undergo a similar process as Guideline Technical Documents, including public consultations through the Health Canada Web site. They are offered as information for drinking water authorities and to help provide guidance in spill or other emergency situations.

Part A of this document provides the guidance for monitoring biological stability of drinking water in distribution systems; Part B provides the scientific and technical information to support this guidance; and Part C provides the references.

EXECUTIVE **SUMMARY**

The drinking water distribution system is the last protective barrier before the consumer's tap. A well-maintained and operated distribution system is therefore a critical component of providing safe drinking water. In order to maintain water quality in the distribution system, it is essential to understand when changes occur. This understanding is achieved through the use of monitoring aimed at assessing the biological stability of water in the distribution system.

Health Canada completed its review of biological stability of drinking water in distribution systems. This guidance document was prepared in collaboration with the Federal-Provincial-Territorial Committee on Drinking Water and describes the significance of biological stability in drinking water distribution systems, monitoring approaches and best practices designed to ensure safe drinking water.

Assessment

Distribution systems represent a complex and dynamic environment, where numerous physical, chemical and biological interactions and reactions capable of significantly impacting water quality can occur. As a consequence, illness, including waterborne outbreaks, has been linked to degradation in distribution system water quality. Despite this, drinking water distribution systems, and the changes in biological stability within them, are generally not characterized or well-understood. The intent of this document is to provide stakeholders, such as provincial and territorial regulatory authorities, decision makers, water system owners and operators and consultants with guidance on the use of monitoring methods to assess the biological stability of water in distribution systems, with the objectives of minimizing public health risks in Canadian water systems.

Part A. Guidance on the biological stability of drinking water quality in water distribution systems

A.1 INTRODUCTION

Water leaving a treatment facility enters an extensive network of pipes (also referred to as watermains), valves, hydrants, service lines and storage facilities, known as the drinking water distribution system, before it reaches the consumers tap. Ideally, there should be minimal change in water quality in the distribution system. This occurs when the water is "biologically stable". For the purposes of this document, biological stability (also known as biostability) refers to the concept of providing consumers with drinking water at a low risk of supporting significant microbiological growth, such that their safety or aesthetic perception is not affected.

Distribution systems represent a complex and dynamic environment—sometimes referred to as a "reactor"—where numerous physical, chemical and biological interactions and reactions involving microorganisms, nutrients and particles, occur. This mixture forms biofilm and loose deposits which can lead to a deterioration in water quality and can result in a variety of problems, including direct (e.g., waterborne outbreaks) and other health risks (e.g., metal exposures), and aesthetic issues (e.g., colour, turbidity or unpleasant taste and odour). Despite this, water quality deterioration occurring during distribution is generally not characterized or well-understood.

A.2 SCOPE AND AIM

The intent of this document is to provide responsible authorities, such as municipalities and water system operators, with an overview of: 1) causes of microbial water quality deterioration in the distribution system; 2) monitoring tools that can be used to assess biological stability; and 3) distribution system management strategies. Although the primary focus of this document is on the component of the distribution system that carries water to buildings, there is a brief discussion of premise plumbing. It is acknowledged that a water utilitys responsibility does not generally include plumbing systems.

The guidance presented here replaces the *Guidance on the Use of Heterotrophic Plate Counts in Canadian Drinking Water Supplies* (Health Canada, 2012).

A.3 CAUSES OF WATER QUALITY DETERIORATION

Water quality deterioration in the distribution system is due to a multitude of factors and mechanisms. Table 1 outlines select factors and mechanisms leading to deterioration in microbial water quality.

Table 1. Select factors that affect microbial water quality in the distribution system.

Presence of microorganisms	Microorganisms are present in all drinking water distribution systems. The majority of these microorganisms are attached to the inner walls of pipes, as part of biofilms and/or loose deposits, where they are protected from disinfectants and other threats.
Type and availability of nutrients	A number of nutrients are present in drinking water distribution systems, and can promote microbial growth, either by serving as fuel for microorganisms or by consuming disinfectant residual. Biofilm and loose deposits constitute a large reservoir of organic nutrients, at concentrations far exceeding those in bulk water.
Temperature	Water temperature is one of the most important factors influencing microbial dynamics in the distribution system. Warmer water temperatures can lead to increased microbial growth, either directly, or via accelerated decay of disinfectant residuals. Temperature fluctuations can also affect microbial attachment.
Pipe material and condition	Biofilms and loose deposits accumulate in all distribution systems regardless of pipe material. However, biofilm biomass tends to be lower on plastic pipes compared to iron. In addition to pipe material, pipe condition can drastically affect water quality in distribution systems. As pipes age, they become prone to leaks and breaks, and more vulnerable to intrusion of contaminants.
Type and concentration of disinfectant residual	Disinfectant residuals possess different capabilities in terms of disinfectant power, reactivity with organic and inorganic material, biofilm penetration, and potential for disinfection by-product formation. Regardless of the type of residual disinfectant used, decreases in concentration in the drinking water distribution system are associated with increased (re)growth.

A.4 MONITORING METHODS AND PARAMETERS

Given the "reactor" nature of drinking water distribution systems, it is essential to monitor changes in biological stability, in order to minimize potential risks to consumers. This has traditionally been done using bacterial indicators (e.g., total coliforms and *E. coli*) and heterotrophic plate count (HPC) monitoring. While these methods are useful and provide information regarding water quality changes that may impact biological stability, they suffer from significant limitations. A variety of other monitoring tools can be used. In this guidance document, monitoring has been categorized as either: 1) basic, 2) operational or 3) advanced in nature. Basic monitoring is consistent with the minimum monitoring recommended for drinking water systems serving the public. Operational monitoring provides an understanding of distribution system dynamics and the factors contributing to water quality deterioration. Advanced methods are presented for those water utilities that have the resources to study water quality in more detail; they may require partnerships between water utilities and universities or advanced commercial laboratories.

Water utilities should use the most appropriate measures, depending on resources, to establish baseline conditions, monitor changes and detect potential or actual contamination events. Monitoring plans should be based on a system-specific assessment, and meet the requirements of the responsible drinking water authority. Suggested parameters/methods to consider are presented in Table 2.

It is important for water utilities to recognize that many of the listed parameters (e.g., disinfectant residual, turbidity) should already be monitored as part of a source-to-tap approach to producing safe drinking water. Other parameters are relatively easy to use and provide rapid results. Some are advanced methods that only large systems will have the resources to apply (e.g., flow cytometry). Once data are collected, they should be analyzed to assess if, and how, distribution system water quality is changing. Water quality goals can then be established. The monitoring plan should also specify actions that should be taken if water quality goals are not met (e.g., increase disinfectant residual).

Table 2. Suggested parameters/methods to assess the biological stability of drinking water in the distribution system.

Type	Suggested parameters/methods
Basic	Bacterial indicators (total coliforms and *E. coli*)
	Disinfectant residual
	Turbidity
	Conductivity
	Pressure
Operational	Temperature
	Microbiological activity—heterotrophic plate count and/or adenosine triphosphate
	pH
	Oxidation-reduction potential
	Colour (apparent and true)
	Nutrient concentrations
	Metals (dissolved and particulate)
	Biofilm formation rate
	Corrosion rate
Advanced	Flow cytometry
	Molecular methods
	Pipe autopsies and characterization of accumulated material
	Water distribution system models

A.5 MANAGEMENT STRATEGIES

A well-maintained and operated distribution system is a critical component of providing safe drinking water. It is recommended that water utilities develop a management plan to understand how the complex biological and physio-chemical interactions and reactions that occur in the distribution system impact biostability and consequently the safety of drinking water. Water utilities may require a multi-faceted approach to effectively balance concomitant objectives (e.g., water quality, physical integrity). Management strategies will be unique to each system based on their design, size and complexity, as well as regulatory requirements. Water utilities are responsible for identifying and managing the full range of risks that may apply to their system(s). Guidance is provided in Part B to assist water utilities.

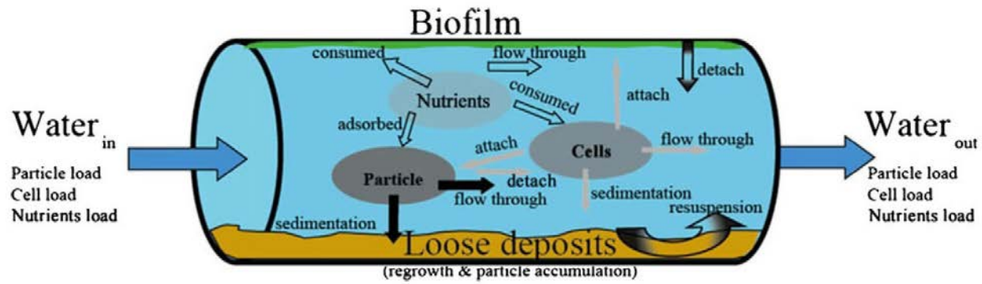
Part B. Supporting Information

B.1 DRINKING WATER DISTRIBUTION SYSTEMS

Water leaving a treatment facility enters an extensive network of pipes (also referred to as watermains), valves, hydrants, service lines and storage facilities, known as the drinking water distribution system, before it reaches the consumers tap. Ideally, there should be minimal change in water quality during distribution until the point of consumption. This occurs when the water is "biologically stable". The concept of biological stability was first introduced in the 1980s (Rittmann and Snoeyink, 1984), and its definition has changed with the evolution of new monitoring approaches (Sibile, 1998; van der Kooij, 2000, 2003; Lautenschlager et al., 2013; Prest et al., 2016a). For the purposes of this document, biological stability refers to the concept of providing consumers with drinking water at a low risk of supporting significant microbiological growth, such that their safety or aesthetic perception is not affected.

Achieving biological stability requires that water utilities produce biologically stable water, and that the distribution system be operated and maintained such that minimal water quality deterioration occurs. It is important to recognize that treated water is not sterile, and contains particles, nutrients, and a microbial load (Figure 1) (Liu et al. 2013a,b). Once this water enters the distribution system, numerous biological and physio-chemical interactions and reactions involving microorganisms, nutrients and particles occur (Figure 1). This is why distribution systems are sometimes referred to as "reactors". These complex and dynamic interactions lead to the formation of biofilm and loose deposits, which contain microorganisms (Figure 1). The result is that water quality can deteriorate and lead to a variety of problems, including direct and other health risks, and aesthetic issues, such as colour, turbidity or unpleasant taste and odour.

Figure 1. The drinking water distribution system as a "reactor": biological and physio-chemical interactions and reactions within the drinking water distribution system.



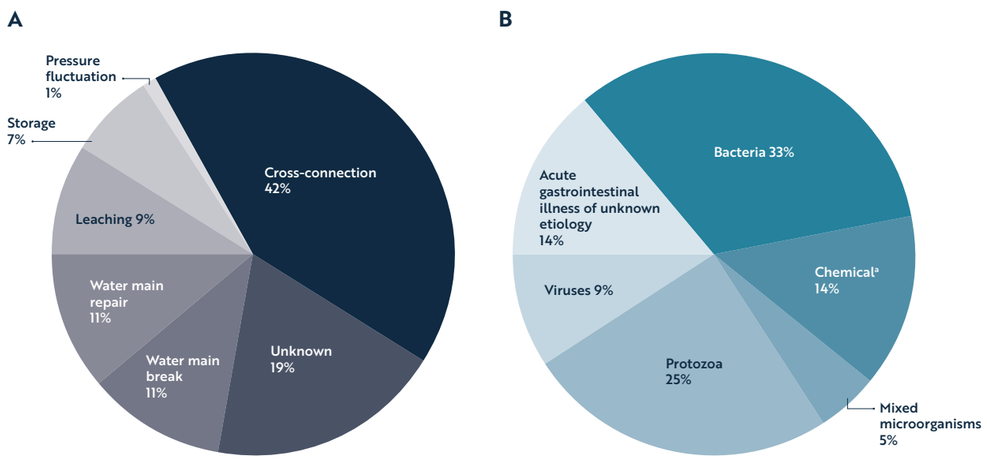
Reprinted with permission from Liu et al., 2013a,b.

B.1.1 Direct health risks

The degree to which water quality deterioration in the distribution system contributes to human illness is difficult to quantify because many events are not detected or recognized. In addition, rates of endemic infectious illness—including waterborne illness—are significantly underreported and underdiagnosed, for a number of reasons (Majowicz et al., 2004; MacDougall et al., 2008; Gibbons et al., 2014). This is further complicated by the fact that, in Canada, there is no national surveillance system specific to waterborne illness and no standardized approach to data collection on sporadic or outbreak cases of waterborne illness (Pons et al., 2015). Instead, provinces and territories report notifiable disease data to the federal government (Public Health Agency of Canada, 2021) based on the disease (e.g., campylobacteriosis) rather than the route of transmission (e.g., waterborne).Thus, there is limited information regarding the magnitude and sources of waterborne illness in Canada, including those attributable to drinking water.

While Canadian surveillance data are scarce, United States (US) surveillance data clearly showa link between distribution system contamination and human illness. Between 1995 and 2014, over 40 waterborne disease outbreaks attributed to distribution system deficiencies were reported in the US (Levy et al., 1998; Barwick et al., 2000; Craun and Calderon, 2001; Lee et al., 2002; Blackburn et al., 2004; Liang et al., 2006; Yoder et al., 2008; Brunkard et al. 2011; Hilborn et al., 2013; Beer et al., 2015; Benedict et al., 2017). These resulted in over 4,800 cases of illness. A meta-analysis of US data, conducted by the World Health Organization (WHO), showed that the majority of waterborne disease outbreaks attributed to distribution system were related to cross-connections (Figure 2); and bacteria were the most common type of etiological agent (WHO, 2014; Renwick et al., 2019). The release of biofilm and deposits in the distribution system, related to a water source change, was implicated in the *Legionella* outbreak that occurred in Flint, Michigan, US, between 2014 and 2015 (Rhoads et al., 2017; Zahran et al., 2018).

Figure 2. Waterborne outbreaks associated with distribution systems in the United States, 1981–2010, by system fault (A) and etiology (B).



Adapted and reprinted with permission from Renwick et al., 2019.

[a] Outbreaks associated with chlorine, copper and lead.

Several international waterborne outbreaks attributable to the distribution system have also been reported (Nygård et al., 2004; Jakopanec et al., 2008; Moreira and Bondelind, 2017; Viñas et al., 2019), and are highlighted in Appendix B. They, like the US outbreaks, show that cross-connections were the main cause of outbreaks in the distribution system; and demonstrate the significant impact of distribution system water quality deterioration on health (Moreira and Bondelind, 2017). An example of this is the extensive outbreak that occurred in Nokia, Finland in 2007. Over 8,400 individuals developed gastroenteritis due to contamination of distributed water by sewage effluent that entered via a cross-connection (at the sewage treatment plant) (Laine et al., 2011; Hrudey and Hrudey, 2014; Moreira and Bondelind, 2017). In addition to cross-connections, distribution system-related outbreaks have been associated with maintenance or repair work of water mains, storage facility contamination, and intrusion of sewage due to leakage (Appendix B; Hrudey and Hrudey, 2004, 2014; Moreira and Bondelind, 2017).

Epidemiological studies have also highlighted an association between the distribution system and illness (Hunter et al. 2005; NRC, 2006; Nygård et al., 2007; Córdoba et al., 2010; Lambertini et al., 2012; Ercumen et al., 2014; Säve-Söderbergh et al., 2017; Viñas et al., 2019). Nygård et al.(2007), for example, reported that breaks and maintenance work in the distribution system led to an increased risk of gastrointestinal illness among consumers. Similarly, Säve-Söderbergh et al.(2017) noted a significant increase in gastrointestinal illness amongst consumers in areas where distribution system incidents, defined as temporary changes in the hydraulic pressure and physical integrity, had occurred. Pressure fluctuations (i.e., transients) represent a serious public health risk as low or negative pressure can allow contaminants to enter the distribution system (Kirmeyer et al., 2001; Besner et al., 2010, 2011).

Models used to explore public health impacts estimate that between 15 and 50% of waterborne gastrointestinal illness can be attributed to distribution system risks (Payment et al., 1991, 1997; Messner et al., 2006; Nygård et al., 2004, 2007; Murphy et al., 2016). In 2021, the US Centers for Disease Control and Prevention (US CDC) estimated that biofilm-associated pathogens, including *Legionella*, non-tuberculous mycobacteria and *Pseudomonas*, accounted for less than 1.5% of all cases of infectious waterborne illness. Despite this, these pathogens contributed a large proportion of the burden of waterborne disease (i.e., greater than 70% of hospitalizations and 90% of deaths linked to waterborne pathogens), and almost 80% of $3.3 billion USD/year of the direct healthcare costs (Collier et al., 2021). This study underscores the potential role of these microorganisms on infectious waterborne disease burden.

B.1.2 Other health risks

Metal precipitates (see Figure 1, particle accumulation), including aluminum, iron, or manganese, can act as an accumulation sink for other contaminants (e.g., arsenic, chromium, copper, lead) (Cantor, 2017). This material can be disturbed and "released" in an uncontrolled manner due to hydraulic disturbances (e.g., fire-fighting activities, watermain breaks, pump station operation) or flushing operations. Table 3 summarizes the concentrations of biological matter (also referred to as biomass) and metal precipitates measured in material removed from two full-scale surface water systems using a range of flushing velocities. Elevated concentrations of microorganisms and metals were measured. Other researchers have reported similar findings for systems using groundwater, surface water and a blend of ground/surface water (Lytle et al., 2004; Seth et al., 2004; Friedman et al., 2010a; Douterelo et al., 2016a; Li et al., 2018). Collectively, these studies demonstrate that significant biomass and metal precipitates can accumulate and lead to deterioration in water quality. This may result in human illness.

The release of microorganisms or metals is also generally associated with discolouration or turbidity events (Prince et al., 2003; Seth et al., 2004; Besner et al., 2008; Husband et al., 2016). Husband and Boxall (2010) reported that cast iron watermains consistently demonstrated higher turbidity with the release of accumulated material compared to polyethylene or polyvinyl chloride (PVC) watermains. Burlingame et al. (2006) reported a direct relationship between turbidity and the release of accumulated material from tuberculated iron pipes. Seth et al. (2004) found elevated turbidity and metals concentrations in material flushed from cast iron, PVC and polyethylene watermains. Thus, consumer complaints of colour, or unpleasant taste and odour, can serve as an indicator of water quality deterioration in the distribution system (Hrudey and Hrudey, 2014).

Table 3. Biological matter and metal precipitate concentrations in hydraulically-mobile material at various flushing velocities (Hill et al., 2018).

Community and pipe material	Velocity (ft/sec)[a]	HPC-R2A[b] (cfu/mL)	Total viable biomass[c] (pg/mL)	Viable bacteria[d] (cells/mL)	Iron (µg/L)	Manganese (µg/L)
Portland, Oregon—cement-lined	4	930	9.3	89,200	4,000	800
	6	750	2.7	28,700[e]	4,400	180
	6	3,300	5.9	54,500[e]	6,400	200
Portland, Oregon—cement-lined with some unlined sections	6	380	4.0	34,000	4,300	330
Portland, Oregon—unlined cast iron	3.0	130	1.2	20,700	3,700	140
	4.8	2,400	19	28,100	26,400	870
	6.0	430	2.0	37,900	15,100	300
	6.0	2,900	54	61,400	16,500	800
	6.4	1,030	4.7	31,300	7,500	210
Seattle, Washington—unlined cast iron	3.0	1,470	270	590,700	193,100	20,600
	4.2	15,500	807	689,100[e]	139,000	30,100
	5.4	3,300	430	577,300	155,700	18,400
	6.0	1,500	280	601,500	199,000	20,900
	6.0	10,400	325	788,300[e]	153,300	11,300

[a] Measured at the flow discharge point using a pitot gauge or magmeter; reported in the units used by the authors. In order to convert to m/s, divide by 3.2808.

[b] Heterothropic plate count (HPC) using R2A medium.

[c] Measured using cellular adenosine triphosphate (cATP).

[d] Measured using flow cytometry (FCM).

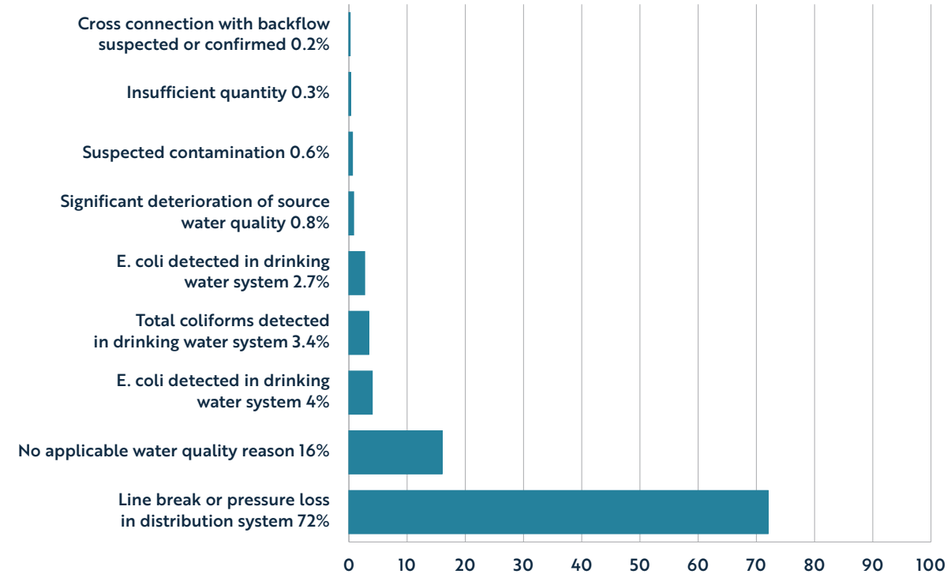
[e] Includes total coliform-positive sample(s).

B.1.3 Distribution systems events or deficiencies

Between 2013 and 2019, watermain breaks and pressure losses in the distribution system were identified as the main reasons for issuing a boil water advisory in Canada, accounting for 72% of advisories (Figure 3). These data are based on analyses of 5,578 records of boil water advisories, issued from 7 of 14 jurisdictions (Health Canada, 2019). A large waterborne outbreak of campylobacteriosis in Norway was attributed to pressure loss and poor distribution system integrity (Jakopanec et al., 2008). The lack of watermain disinfection following repair was also a contributing factor.

Fox et al. (2016) demonstrated that contaminants external to a small leak (5 mm diameter) in a pressurized pipe could enter the pipe and be transported within the system when negative transient pressures occur. Low and negative transient pressures can occur as a result of distribution system operation/maintenance or unplanned events such as power outages or watermain breaks. Low and negative transient pressures also allow contamination to enter the distribution system from cross-connections and/or backflow from domestic, industrial or institutional facilities (Gullick et al., 2004).

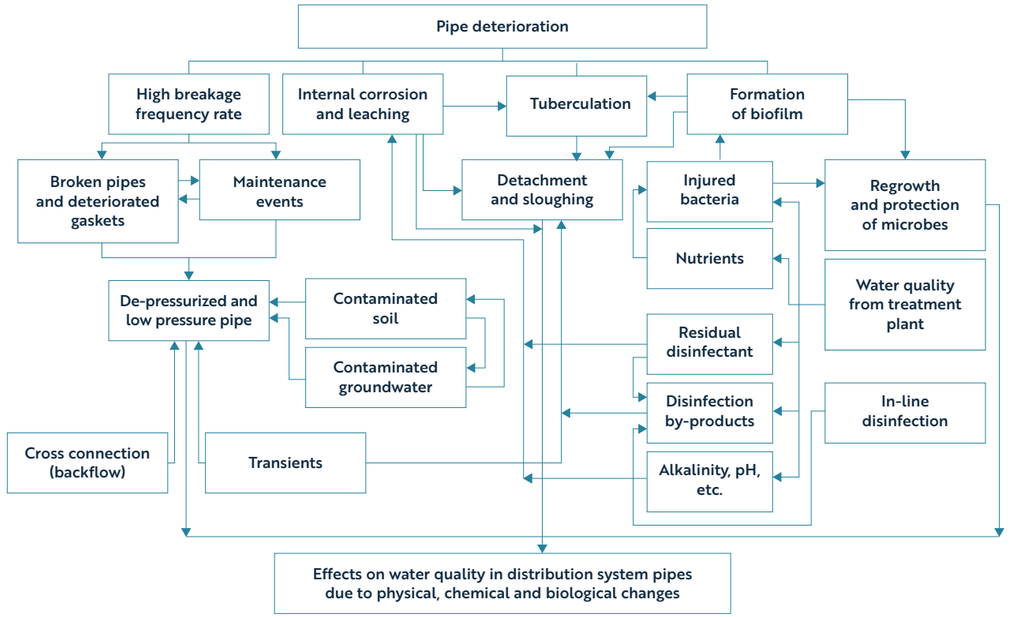
Figure 3. Reasons for issuing boil water advisories on public water supplies in Canada (Health Canada, 2019).



B.2 CAUSES OF WATER QUALITY DETERIORATION

Given the "reactor" nature of drinking water distribution systems, and the resulting potential for water quality deterioration, it is important to understand the causes of this deterioration. Water quality deterioration in the distribution system is complex, and a multitude of factors and mechanisms are involved (Figures 4 and 5). A brief discussion of select factors and mechanisms leading to deterioration in microbial water quality is provided below. For a more comprehensive review, please refer to LeChevallier, 1999; van der Kooij and van der Wielen, 2014; WHO, 2014; LeChevallier et al., 2015a,b; Prest et al., 2016a,b,c.

Figure 4. Factors contributing to deterioration of water quality in the drinking water distribution system



Source: Sadiq et al., 2009. Adapted and reprinted with permission. © AwwaRF.

B.2.1 Presence of microorganisms

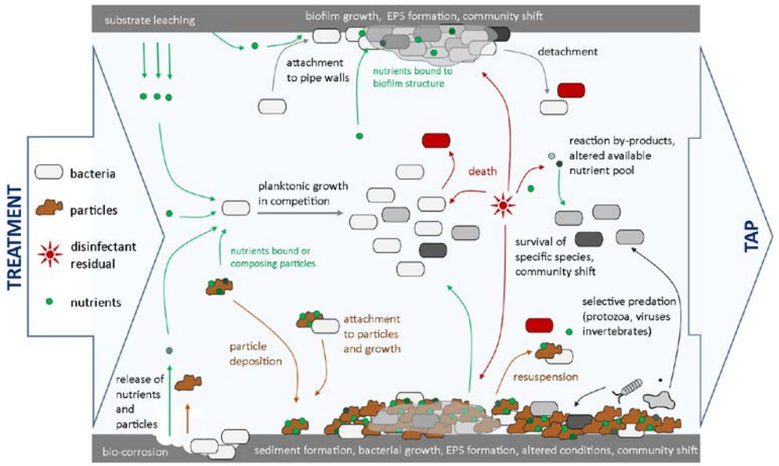
Microorganisms are present in all drinking water distribution systems. They are present for two main reasons: 1) they are introduced into the distribution system or 2) conditions in the distribution system favour the (re)growth of microorganisms already present. Microorganisms can enter the distribution system by surviving the water treatment process or by intrusion. Intrusion occurs when there is an integrity breach, such as a pipe break or leak, and pressure transients (LeChevallier et al., 2011). Several studies have demonstrated the potential for microbial contaminants to enter the distribution system (Karim et al., 2003; LeChevallier et al., 2003; Besner et al, 2010, 2011; Yang et al., 2011; Ebacher et al., 2012; Fontanazza et al., 2015; Fox et al., 2016). Multiple factors and mechanisms can promote microbial (re)growth, and are discussed in subsequent sections (Besner et al., 2012; Lee, 2013; LeChevallier et al., 2015a; Prest et al., 2016a,b,c; AWWA, 2017a).

The majority of microorganisms in drinking water distribution systems are attached to internal pipe surfaces (Flemming et al., 2002), as part of biofilm and/or loose deposits. The remainder exist as transient populations in the bulk water (Liu et al., 2013a,b, 2014, 2016, 2017; Proctor and Hammes, 2015) (Figures 1 and 5). Attached microorganisms can be retained for a longer period of time than transient microorganisms—i.e., years versus the time it takes for water to flow through (Liu et al., 2017). The combined genetic material of these microbial populations is known as the microbiome. Microbiomes are very heterogeneous, as well as time and site-specific both within and between distribution systems (Gomez-Alvarez et al., 2012; Chao et al., 2013, 2015; Delafont et al., 2013; Wang et al., 2014a,b; Zhang et al., 2017).

Attached microorganisms (in biofilm and loose deposits) are typically encased in a matrix of extracellular polymeric substances (EPS) that contains both organic and inorganic matter (Prest et al., 2016a; Liu et al., 2016; WRF, 2017). The EPS matrix encompasses a wide range of compounds—polysaccharides, proteins, nucleic acids and lipids—and can account for over 90% of the total organic matter in the biofilm and loose deposits (Christensen and Characklis, 1990; Flemming and Wingender, 2010; Liu et al., 2017). The EPS composition determines important properties of the biofilm such as how well it adheres to the pipe wall, how it moves under shear forces, erodes or sloughs off and how well it adsorbs dissolved and particulate substances from the bulk water (Nielsen et al., 1997; Wingender et al., 1999). The EPS structure provides protection against predators and disinfectants, and aids in uptake and utilization of nutrients (LeChevallier et al., 1988; Flemming and Wingender, 2010; Prest et al., 2016a). In addition, the polysaccharides and proteins within the EPS are important precursors to disinfection by-product formation (Wang et al., 2013).

Biofilms provide a habitat for the survival and growth of microorganisms, including pathogens (Health Canada, 2021a). A variety of enteric pathogens have been detected in biofilms (Park et al., 2001; Howe et al., 2002; LeChevallier et al., 2003; Chang and Jung, 2004; Berry et al., 2006; September et al., 2007; Gomez-Alvarez et al., 2015; Revetta et al., 2016); where they can accumulate and be released over an extended period of time (Howe et al., 2002; Warnecke, 2006; Wingender and Flemming, 2011). Non-enteric pathogens have also been detected in biofilms, including opportunistic premise plumbing pathogens (OPPPs), such as *Legionella pneumophila* and non-tuberculous mycobacteria (e.g., *M. avium, M. intracellulare*) (Norton et al., 2004; Pryor et al., 2004; Vaerewijck et al., 2005; Feazel et al., 2009; Falkinham et al., 2015; Wang et al., 2017). These organisms have adapted to grow and persist in distribution and plumbing system biofilms and have been linked to several outbreaks (Pruden et al.,2013; Beer et al., 2015; Falkinham et al., 2015; Benedict et al., 2017), including the 2014-15 Legionnaires disease outbreak in Flint, Michigan, US (Zahran et al., 2018). They represent a significant challenge to the water industry and building managers (see Section B.7).

Figure 5. Microbial dynamics in a drinking water distribution system pipe



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B.2.2 Type and availability of nutrients

A number of nutrients may be present in drinking water distribution systems, and can promote microbial growth, either by serving as fuel for microorganisms or by consuming disinfectant residual (NRC, 2006). The biodegradable portion of natural organic matter, referred to as biodegradable organic matter (BOM), for example, impacts distribution system water quality by providing a source of nutrients that contributes to microbial regrowth and biofilm development (Huck, 1990). Concentrations of BOM (e.g., assimilable organic carbon and biodegradable organic carbon) are only one component influencing changes in water quality in the distribution system (Prest et al., 2016a,b,c). Other nutrients have been identified as having roles in controlling microbial growth in the distribution system, including phosphorus, nitrogen, ammonia, manganese, sulphate, iron and humic substances (Camper, 2004, 2014; Coetser et al., 2005; Prest et al., 2016a,b,c). For example, *Legionella* requires specific nutrients for growth including iron (Percival and Williams, 2014). They can adapt to fluctuating nutrient conditions by differentiating into cell types that vary in their infectivity and resistance to disinfection (Robertson et al., 2014; NAS, 2019).

It is also important to recognize that biofilm and loose deposits (Figure 1) constitute a large reservoir of organic nutrients (Zacheus et al., 2001; Liu et al., 2013a,b) with concentrations 200 to 2 000 times higher than the bulk water (Gauthier et al., 1999). This material is available to fuel (re)growth and consume disinfectant residual (Chandy and Angles, 2001).

B.2.3 Temperature

Distribution system water quality can diminish considerably because of water temperature. In fact, water temperature is one of the most important factors influencing microbial growth (LeChevallier et al., 1990, 1996; Camper et al., 2000; van der Kooij et al., 2003; Baribeau et al., 2005; LeChevallier et al., 2015a,b; Health Canada, 2021b). In an 18-month study involving 31 full-scale systems (17 using chlorination and 14 using chloramination), higher coliform bacteria detections were reported in warmer months (LeChevallier et al., 1996). Similarly, Schleich et al. (2019) found total cell counts (measured using flow cytometry—see B.3.4.1) increased up to 5.24-fold in summer in a 12-month study of a full-scale system using chloramination.

Warmer water temperatures can also affect microbial growth via their effect on disinfectant residual. They can lead to two conflicting effects, namely: 1) increased efficacy of chemical oxidation; and 2) accelerated decay of the disinfectant residual (Li et al. 2003; van der Wielen and van der Kooij, 2010). Thus, increases in water temperature generally lead to lower biocidal effects of the disinfectant residual (Baribeau et al., 2005). LeChevallier et al. (2015a,b) observed that the biofilm formation rate was 25 times greater at temperature >15 °C compared to <15 °C in a 14-month study of six full-scale systems—three using chlorination and three using chloramination (see B.3.2.7). Elevated temperatures can also affect the solubility of metals (e.g., copper) present in the distribution systems, and result in increased leaching and corrosion (Singh and Mavinic, 1991; Boulay and Edwards, 2001; Sarver and Edwards, 2011). Temperature fluctuations can also affect biofilm attachment because of changing EPS production (Liu et al., 2016).

Climate change is expected to increase water temperature. This may exacerbate other anticipated climate-related changes, such as increased nutrient loading. This, in turn, can promote microbial growth and the survival of pathogens in distribution system biofilms. In addition, this may result in longer periods at temperatures that trigger water quality deterioration (Levin et al., 2002).

B.2.4 Pipe material and condition

Pipe material can affect microbial regrowth, and biofilm formation and composition. While biofilm can form on all pipe materials, biofilm biomass tends to be higher on corroded iron pipes as compared to uncoated plastic pipes, such as PVC and polyethylene (Niquette et al., 2000; Baribeau et al., 2005; Wang et al., 2012; Douterelo et al., 2014b; Wang et al., 2014a; Fish et al., 2016). Differences in surface characteristics including roughness and area, as well as the chemical properties of pipes, influence microbial adhesion. In the case of surface roughness for example, rougher surfaces allow microorganisms to adhere more quickly (Fish et al., 2016). Pipe material also appears to influence microbial diversity (also referred to as richness) and stability, although there is debate as to which material has the greatest impact on these parameters.

In addition to pipe material, pipe condition can significantly affect the microbial quality of drinking water in the distribution system. Pipe corrosion can generate a significant disinfectant demand, making it difficult to maintain disinfectant residual concentrations (Health Canada, 2009a). In the case of iron pipes, for example, corrosion can be exacerbated by the presence of iron-oxidizing bacteria. These bacteria are responsible for a form of microbially induced corrosion, resulting in the formation of raised outgrowths of ferrous oxide, called tubercles. Tubercles can harbour microorganisms, including opportunistic pathogens (Emde et al., 1992; US EPA, 2002; Batté et al., 2003; NRC, 2006; Teng et al., 2008); and exhibit a high disinfectant demand. The tubercles can also generate colour, turbidity, tastes and odours, as well as reduce hydraulic efficiency (Husband and Boxall, 2010).

As pipes age, they may become more prone to leaks and breaks, and more vulnerable to intrusion of contaminants (OConnor, 2002; Moe and Rheingans, 2006; Qureshi and Shah, 2014). During low or negative pressure events, contaminants surrounding the pipes can be drawn in through leaks in the system (see Section B.1.3). Aging water infrastructure is a significant threat to water safety in Canada (Canadian Infrastructure Report Card, 2016). In Ontario, for example, many water systems were constructed in the 1960s and 1970s, (MacDonald, 2001) and, as such, will be nearing the end of their life span, which averages around 50 to 70 years (Tafuri and Field, 2010). Pipes installed during the 1960s and 1970s have also been associated with an increased likelihood of failure because of the type of material used, and poor installation practices (Besner et al., 2001; MacDonald, 2001). In other parts of Canada, pipes date back to before 1867 (Besner et al., 2001; Saint John Water, 2018).

B.2.5 Type and concentration of residual disinfectant

Residual disinfectant type and concentration also affect distribution system microbial water quality. In Canada, the majority of water utilities use free chlorine as a residual disinfectant; while the rest use chloramines (Health Canada, 2009b). These disinfectants possess different capabilities in terms of disinfectant power, reactivity with organic and inorganic material and biofilm penetration. These differences mean that the residual disinfectant is generally consumed within three days when using free chlorine compared to seven days when using chloramines (Baribeau et al., 2005). In the case of chloramines, free ammonia is released as the residual is consumed (i.e., decays); and this can lead to nitrification, the microbiological process whereby ammonia is sequentially oxidized to nitrite and nitrate by ammonia-oxidizing bacteria and nitrite-oxidizing bacteria, respectively (Wilczak, 2006). This can result in growth of nitrifying bacteria, leading to a loss in disinfectant residual and increased biofilm production, which further escalates the chlorine demand, ammonia release and microbial regrowth (Wilczak et al., 1996; Pintar and Slawson, 2003; Strickhouse et al., 2006; Wilczak, 2006; Scott et al. 2015; Bradley et al., 2020; Tolofari et al., 2020).

Regardless of the type of residual disinfectant used, decreases in concentration in the drinking water distribution system are associated with increased (re)growth (Codony et al., 2005). There is increasing recognition that higher minimum disinfectant residual concentrations are required to control (re)growth (Gagnon et al., 2008; Gillespie et al., 2014; Rand et al., 2014; LeChevallier et al a., 2015a,b). Collectively, these studies indicate that disinfectant residual concentrations in the order of 1.0 mg/L free chlorine (for systems that chlorinate) and 1.8 mg/L total chlorine (for systems that chloraminate) are required to control (re)growth. LeChevallier et al. (2015b) stated that the differences between operating above and below these thresholds were stark—that is, the biofilm formation rate (see Section B.3.2.7) was six and 23 times higher when operating below the noted free and total chlorine residual concentrations, respectively.

B.3 MONITORING METHODS AND PARAMETERS

Drinking water distribution systems are complex and dynamic environments. In order to understand changes in biological stability, a monitoring program (see Section B.4) should be designed and implemented to establish baseline conditions, monitor changes and detect on-going or potential contamination events. Comprehensive monitoring programs are recommended (Cantor, 2017, 2018; Hill et al., 2018) to obtain a better understanding of the dynamics in the drinking water distribution system, thereby increasing the likelihood of detecting periods of higher risk. Multi-parametric approaches to monitoring water quality in the distribution system are supported in the literature (Escobar and Randall, 2001; Hammes and Egli, 2005; van der Kooij, 2000; Berney et al., 2008; Vital et al., 2010, 2012; Hammes et al., 2011; Lautenschlager et al., 2013; Douterelo et al., 2014a; van der Kooij and van der Wielen, 2014; LeChevallier et al., 2015a,b; van der Kooij et al., 2015; Van Nevel et al., 2017).

For the purposes of the following discussion, potential methods or parameter analyses have been categorized as either: 1) basic, 2) operational or 3) advanced in nature.

B.3.1 Basic monitoring

The Guidelines for Canadian Drinking Water Quality: Guideline Technical Documents for *Escherichia coli* (*E. coli*) and for Total Coliforms (Health Canada, 2020a,b) recommend that bacterial indicators be monitored in conjunction with other parameters such as disinfectant residual, turbidity and pressure. Monitoring of conductivity is recommended to complement turbidity (Health Canada, 2021c). The parameters described in this section should, at a minimum, be monitored as part of a source-to-tap approach to producing safe drinking water. Once data are collected, they should be analyzed to determine their variability as discussed below.

B.3.1.1 Bacterial indicators

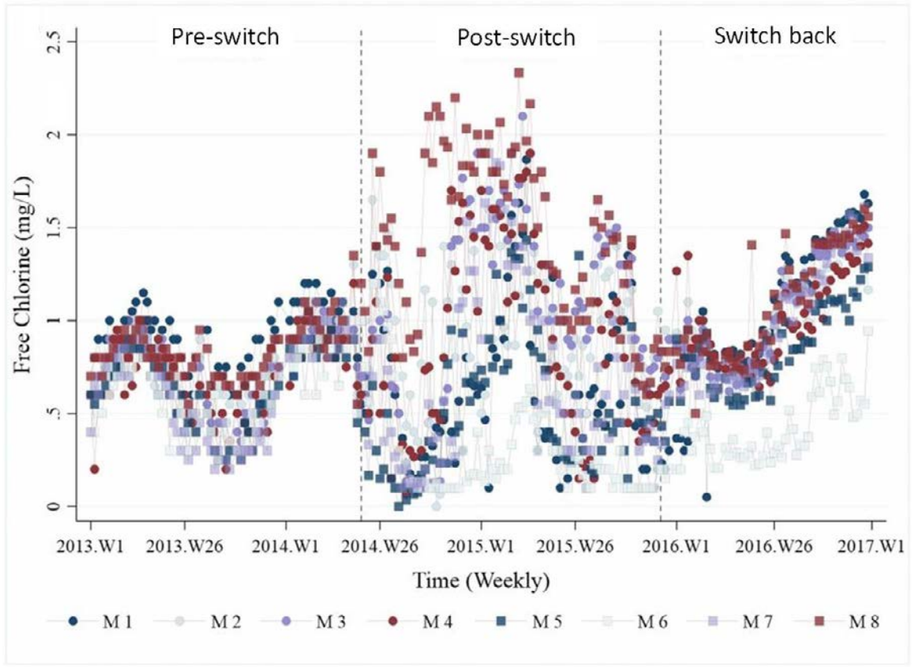
Routine monitoring of total coliforms and *E. coli* is a fundamental part of the source-to-tap approach to producing safe drinking water and forms the basis for most regulatory compliance monitoring in Canada (CCME, 2004). These indicators are used to indicate potential unsanitary conditions, physical integrity issues and (re)growth in the distribution system (Health Canada, 2020a,b). However, because they are seldom detected, they provide very little information about the microbiome (Hargesheimer, 2001; US EPA, 2016a). Hence it is recommended that they be paired with other parameters.

B.3.1.2 Disinfectant residual concentrations, turbidity and conductivity

Measuring the disinfectant residual and turbidity in the drinking water distribution system is important and should be done when bacterial indicator samples are collected (Health Canada, 2020a,b). Disinfectant residual concentration is an indirect measure of microbial abundance for both chlorinated and chloraminated systems. Decreases serve as an essential sentinel for water quality changes, such as increased microbial activity or physical integrity issues (LeChevallier et al., 1996, 1998; Haas, 1999; NRC, 2006; Nescerecka et al., 2014; Prest et al., 2016a; Health Canada, 2020a,b; Kennedy et al., 2021). Turbidity provides an indication of particulate solids in the water. A helpful corollary is conductivity, which provides an indication of the dissolved solids in the water (US EPA, 2009, 2018a; Health Canada, 2021c). These parameters should be analyzed in the field. Online or multi-parameter in-line sensors are available to conduct real-time monitoring of these and other distribution system parameters (Frey and Sullivan, 2004; LeChevallier et al., 2011; Durand et al., 2016; AWWA, 2017a; US EPA, 2018a).

Once data are collected, they should be analyzed to determine their variability. Variability, as measured by the coefficient of variation (defined as the standard deviation divided by the average for a data set) is a useful indicator of water quality stability (LeChevallier et al., 2015b). Lower values indicate less variability. Variability can also be visually assessed by graphing water quality data by sampling site as shown in Figure 6. This graph shows free chlorine residuals for eight monitoring locations in Flint, Michigan before and after the water source was changed. It clearly shows increased variability in free chlorine concentrations after the water source was changed and a return to more stable conditions with the switch back to the old source (Zahran et al., 2018). Water utilities can use their data to graph trends, establish target goals and set control limits—known as control charts (Cantor and Cantor, 2009).

Figure 6. **Free chlorine concentrations measured at eight monitoring stations (M1-M8) in Flint, Michigan before and after the water source was changed.**



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B.3.1.3 Pressure

Water pressure is a critical requirement to prevent the entry of contamination into the distribution system (Kirmeyer et al., 2001; AWWA, 2017a). As a result, guidance and/or design standards from provincial/territorial jurisdictions or industry associations outline minimum requirements (ACWWA, 2004; GLUMRB, 2012; AWWA, 2017a, 2018). Pressure fluctuations (i.e., transients) are impossible to avoid as they originate from routine activities such as a pump starting or stopping, rapid opening or closing of valves and hydrants, watermain breaks and power outages (Kirmeyer et al., 2001). Furthermore, a moderate pressure transient of 50–200 kPa (7–29 psi) can cause a watermain to fail (Rathnayaka et al., 2016).

In light of the risk associated with transients, the American Water Works Association (AWWA 2017a) recommends continuous monitoring throughout the distribution system to confirm that water pressure is within targeted ranges. AWWA (2018) recommends a minimum of two monitoring sites per pressure district—one at the site representing the lowest pressure and the other at the highest pressure. For large pressure districts, more monitoring locations may be necessary (LeChevallier et al., 2011, 2014). Advances in high-speed pressure measuring equipment (e.g., multiple readings per second) has facilitated more extensive monitoring and improved understanding of pressure transients (Friedman et al. 2004; Besner et al., 2010; Ebacher et al., 2011; Rathnayaka et al., 2016). Portable equipment also allows for increased system coverage (Sutherns, 2020; Hamilton and Nikolica, 2021).

B.3.2 Operational monitoring

It is important that water utilities integrate operational monitoring into their programs to establish baseline conditions (e.g., normal variations not requiring action), target goals and set control limits. Thus, operational monitoring is typically more comprehensive than regulatory-based monitoring (Hill et al., 2018). The parameters discussed below have been identified as useful measures for biostability (LeChevallier et al., 2015a,b; Cantor, 2017, 2018; Hill et al., 2018). Water utilities are responsible to identify the full range of operational monitoring requirements for their system(s).

B.3.2.1 Temperature

Based on the broad range of impacts that temperature can have (see Section B.2.3) and because climate change is forecast to increase water temperature, water utilities should monitor water temperature in the distribution system (Health Canada, 2021b). Thus, system-specific relationships between temperature and other parameters can be used to develop management strategies (LeChevallier et al., 2015a,b). Temperature should be measured in the field. Online instruments are also available (Buchberger et al., 2003).

B.3.2.2 Microbiological activity

Heterotrophic Plate Count (HPC)

Detection of heterotrophic bacteria has traditionally been used to assess general bacteriological water quality, including that in the distribution system (Chowdhury, 2012; Health Canada, 2012). These bacteria are naturally present in the environment, including water and are not associated with fecal contamination. They can be measured using HPCs (APHA et al., 2017). Standard HPC methods use colony formation on culture media to approximate the concentration of heterotrophic bacteria in a drinking water sample (Lillis and Bissonette, 2001; Reasoner, 2004; APHA et al., 2017). Although no single growth medium, incubation temperature or incubation time will ensure the recovery of all heterotrophic bacteria, including those that might be injured, use of R2A agar has proven most sensitive (Deininger and Lee, 2001; Uhl and Schaule, 2004; Gagnon et al., 2007; Rand et al., 2014, AWWA, 2017a).

Heterotrophic plate count can be correlated to changes in distribution system water quality (Hargesheimer, 2001; Gagnon et al., 2007; Rand et al., 2014). Unexpected increases in the HPC baseline range can indicate a disruption or contamination in the distribution system. For example, a decrease in disinfectant residual is generally associated with an increase in HPC. Despite its long history of use, low cost, and simplicity, the HPC method has several disadvantages. Among these is the requirement to not exceed an 8-hour holding time, and the time to obtain results (2-7 days). Another significant drawback is that heterotrophic bacteria represent neither the abundance nor the composition of bacteria in the drinking water (Van Nevel et al., 2017). In fact, the consensus in the literature is that the fraction of bacterial cells detected using HPC is less than one percent of the total bacterial concentration in drinking water (WHO, 2003; Prest et al., 2016a; Van Nevel et al., 2017). This means that this method greatly underestimates the concentration and diversity of bacteria present in the drinking water distribution system. Given the limitations of HPC, the water industry has been investigating alternative methods.

Adenosine triphosphate (ATP) analysis

Adenosine triphosphate measurements are gaining popularity as an indicator of total viable biomass in the distribution system (Bourbigot et al., 1982; Ochromowicz and Hoekstra, 2005; Whalen et al., 2006; Siebel et al., 2008; Hammes et al., 2010; van der Wielen and van der Kooij, 2010; Nescerecka et al., 2016; Whalen et al., 2018); assays are low cost, easy to perform, and provide results in a matter of minutes. Adenosine triphosphate is an energy molecule produced by all living organisms, and can be used as an indicator of microbial activity. A standard test method is available for detection of ATP content in microorganisms in water (ASTM International, 2015); and commercial kits, compliant with this method, are available.

The method consists of filtering water samples, followed by addition of a lysing agent in order to release cellular-ATP (cATP) from microbial cells captured on the filter (ASTM International, 2015). Luciferin-luciferase, a bioluminescence enzyme, is added, and the resulting light intensity is measured using a luminometer. The relative light units emitted are converted by comparison with an ATP standard, to provide the concentration of cATP in the sample (in pg ATP/mL) (ASTM International, 2015). This concentration is proportional to the number of viable microbial cells present in the sample. The method normally detects cATP concentrations ranging from 0.1 pg cATP/mL (i.e., detection limit) to 4×10^6 pg cATP/mL (i.e., upper limit) in 50 mL water samples (ASTM International, 2015). Kennedy et al. (2021) reported that cATP was strongly correlated to intact cell counts (measured using flow cytometry – see Section B.3.4.1) for both chlorinated and chloraminated systems. Other researchers have found similar results (Nescerecka et al., 2014; Prest et al., 2016c; Van Nevel et al., 2017).

Adenosine triphosphate measurements should be graphed and trends should be used and interpreted in conjunction with other monitoring results (Siebel et al., 2008; Hammes et al., 2010; Douterelo et al., 2014a; Nescerecka et al., 2014; Van Nevel et al., 2017). For example, ATP measurements along with disinfectant residual trends (e.g., are they decreasing), can very quickly provide an indication of increased microbial activity that requires follow-up actions. Baseline cATP concentrations will be unique to each system (Stoddart, 2020).

Cellular-ATP concentrations above 1 pg/mL have been used to trigger actions to prevent increased microbial activity in full-scale chlorinated (Hill et al., 2018) and chloraminated (Ballantyne and Meteer, 2018) distribution systems. Others have published full-scale applications of ATP measurement (Bourbigot et al., 1982; Delahaye et al., 2003; Cantor et al., 2012; LeChevallier et al., 2015a,b; Skadsen et al., 2015; Shurtz et al., 2017; McIlwain, 2020).

B.3.2.3 pH and oxidation-reduction potential

pH and oxidation-reduction potential (ORP) are critical parameters that influence the life cycle of microorganisms and the solubility of metals in the distribution system. Data from these parameters can help explain trends and variations in distribution system water quality. For example, an oxidative state (ORP >100 mV) will support aerobic microbial activity whereas a reductive state (ORP <0 mV) will encourage anaerobic microbial activity (AWWA, 2015a). An oxidative state indicates the presence of oxidizing agents such as dissolved oxygen and at high ORP values, the presence of chemical disinfectants such as chlorine (Goncharuk et al., 2010; AWWA, 2015a). High ORP indicates a water quality that is not conducive to microbial growth (Cantor, 2018).

Microbial activity can lower the pH in the distribution system due to biofilm respiration which produces carbon dioxide. This, in turn, can lead to corrosion and the release of metals (e.g., lead, copper) (AWWA, 2011). Higher pH, on the other hand, results in lower ORP. Copeland and Lytle (2014) presented the ORP for commonly used oxidizing agents under various pH conditions. For free chlorine, a concentration of ~0.2 mg/L achieved an ORP of 600 mV at pH 7 and 8 whereas at pH 9, between 0.5–0.8 mg/L was required (values interpreted from a graph). The authors also compared ORP values at pH 8—to achieve an ORP of 600 mV, 1.1–1.7 mg/L of monochloramine was necessary compared to ~0.2 mg/L for free chlorine (values interpreted from a graph). Thus, ORP provides a rapid, single-value result that is comparable between distribution systems regardless of the disinfectant residual concentration or pH.

Overnight stagnation can trigger a change in ORP because the biofilm and loose deposits exert a chemical oxidant demand (see Section B.2.2). This, in turn, can lead to an increase in metals concentrations (Blain, 2014; Blain and Friedman, 2014; Friedman, 2014). The authors found that after 15 hours of stagnation, iron increased from <0.1 mg/L to 1.1 mg/L and manganese increased from <0.02 mg/L to 0.07 mg/L. An ORP of 700–900 mV was required to control metals concentrations; this correlated to free chlorine residuals of 0.6–0.8 mg/L. ORP versus pH relationships (known as Pourbaix diagrams) help predict the speciation of metals to better control chemically-influenced processes in the distribution system (i.e., corrosion, adsorption/desorption) (Copeland and Lytle, 2014). The WHO (2011a) recommends that the ORP necessary to ensure effective oxidation be determined on a system-specific basis.

These parameters should be analyzed in the field as changes can occur very quickly if water samples are in contact with air. Online instruments are also available (Frey and Sullivan, 2004; US EPA, 2009; US EPA, 2018a).

B.3.2.4 Colour

Colour can be associated with biofilm or metal releases (Husband and Boxall, 2010) and can be a useful indicator of water quality changes. The presence of suspended particles (e.g., clay, iron and manganese oxides) can give water the appearance of colour. Apparent colour applies to unfiltered samples and is a useful measure to assess the presence of iron and manganese oxides in the distribution system (Reiber and Dostal, 2000). A filtered sample is operationally defined as "true colour" (APHA et al., 2017) and measures colour that is due to the presence of dissolved organic matter. The comparison of apparent and true colour can help water utilities determine if colour complaints are due to suspended particles or dissolved organic matter (Health Canada, 2020c).

Online, portable and bench top analyzers are available to measure colour continuously, in the field or at the laboratory.

B.3.2.5 Nutrient concentrations

As nutrients fuel microbial (re)growth and biofilm development, water utilities should aim to minimize their concentration in treated water and have a good understanding of their concentrations in the distribution system. Water utilities that chloraminate should be particularly vigilant as free ammonia is released in distribution and premise plumbing systems as the residual decays; this can lead to significant (re)growth (Strickhouser et al., 2006; Bradley et al., 2020; Tolofari et al., 2020).

It is recommended that total or dissolved organic carbon be monitored (LeChevallier et al., 2015a,b; Cantor, 2017; Hill et al., 2018). For water utilities that chloraminate, it is important to monitor for nitrification events (e.g., total and free ammonia, nitrite, nitrate). For water utilities using phosphate-based corrosion inhibitors, monitoring throughout the distribution system is necessary to ensure a consistent corrosion inhibitor concentration. Online and portable analyzers are available to obtain rapid results.

B.3.2.6 Metals

The complex and dynamic environment found within distribution systems results in metal precipitates being bound into the biofilm and loose deposits. Changes in water quality conditions (e.g., disinfectant residual, ORP, pH) and hydraulic disturbances (e.g., hydrant flushing, watermain breaks, leak repair, firefighting activity) can cause an increase in metals concentrations.

At a minimum, monitoring should be conducted for metals that are major accumulation sinks (e.g., aluminum, iron and manganese) for other health-based contaminants. In addition, it is recommended that key health-based contaminants that are known to accumulate be monitored (e.g., arsenic, lead and any other site-specific parameters for which treatment is in place). Some laboratories offer a long list of metals for one price per sample. In this case, the full scan of metals is recommended to obtain useful information regarding scale formation and dissolution (Cantor, 2017). Online and portable analyzers are also available to obtain rapid results.

Determining the concentration of both the dissolved and particulate fractions is recommended (Cantor, 2017). Knowing whether metals are present in dissolved versus particulate form is helpful to assess the fate and transport of metals within the distribution system and to diagnose potential mechanisms leading to upsets or release events. For example, an increase in particulate metals concentrations suggests the need for watermain cleaning (e.g., unidirectional flushing) to remove hydraulically-mobile material. An increase in dissolved metals concentrations may require tighter control over treated water quality (e.g., pH, phosphate).

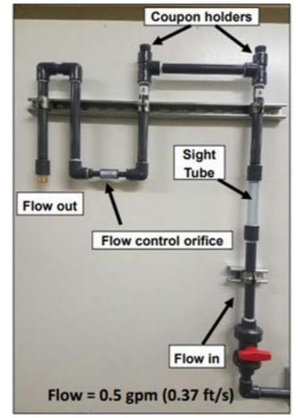
In order to determine dissolved metals concentrations, samples should be filtered at the time of collection (not at the laboratory). If this is not possible, the sample should be collected and delivered to the laboratory without delay for filtering and acidifying (APHA et al., 2017). For distribution system monitoring, it is acceptable to consider the particulate form to be the difference between the total and dissolved metal concentration.

B.3.2.7 Biofilm formation rate and corrosion rate

The biofilm formation rate assesses the rate and extent of (re)growth—aerobic or anaerobic—that occurs on coupons placed in a flow-through apparatus such as the one shown in Figure 7 (van der Kooij, 1999; van Lieverloo et al., 2012; LeChevallier et al., 2015b; Hooper et al., 2019). Metal coupons can be used to simultaneously measure the corrosion rate since corrosion control is necessary to minimize water quality deterioration (LeChevallier et al., 2015b; Cantor, 2017). Alternatively, coupons made of glass (van der Kooij, 1999) or polycarbonate (Hooper et al., 2019) can be used to only measure the biofilm formation rate.

The apparatus shown in Figure 7 provides a simple, easy and cost-effective way to compare the (re)growth and corrosion rate at different locations in the distribution system where it can be installed (e.g., pump station, public buildings). Water flows across the coupon at a controlled flow rate and for a set time to allow for comparisons between sites. Microorganisms attach, form a biofilm and trigger water quality changes. For the biofilm formation rate, the coupons are collected after two weeks and the quantity of ATP is measured (Hooper et al., 2019). For the corrosion rate, measurement options include monthly coupon weight loss and/or linear polarization resistance using mild steel electrodes (LeChevallier, 2015a,b). The corrosion rate should be assessed over an extended period of time, not for short term changes (AWWA, 2017b).

Figure 7. Simple flow-through apparatus.



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System-specific relationships between the biofilm formation and corrosion rates can then be established with disinfectant residual and temperature (LeChevallier et al., 2015a,b).

B.3.3 Advanced methods

B.3.3.1 Flow cytometry (FCM)

Flow cytometry is the most established research method for monitoring of microbial water quality in the distribution system (Douterelo et al., 2014a; Van Nevel et al., 2017; Safford and Bischel, 2019), and has been applied to the study of multiple full-scale systems (Lautenschlager et al., 2013; El-Chakhtoura et al., 2015; Prest et al., 2016c; Nescerecka et al., 2018; Schleich et al., 2019; Favere et al., 2020; Kennedy et al., 2021). This method characterizes and quantifies suspended particles, including microbial cells, using an instrument called a flow cytometer. In short, particles, including microbial cells, in a sample are stained through the addition of a fluorescent dye (e.g., SYBR Green I), and this sample is then injected into the flow cytometer. Once in the flow cytometer, particles pass, one at a time, through a laser beam (Shapiro, 2003; McKinnon, 2018; Figure 8). The laser beam excites fluorescent particles, which then emit light at a higher wavelength.

Flow cytometry data can by analysed in different ways, using various "gating" strategies. Gates are placed around populations of cells with similar characteristics, in order to investigate and quantify them. Flow cytometric cell counts are reported as either total cell counts and/or intact cell counts. Intact cell counts are determined when additional staining is done, using nucleic acid-binding dyes, such as propidium iodide (PI), in order to distinguish between intact cells and membrane-damaged cells (Ramseier et al., 2011).

While there appear to be many advantages to using FCM, including that it provides the most accurate representation of the microbiome (Van Nevel et al., 2017; Kennedy et al., 2021); there are also a number of disadvantages associated with its use (Table 4). Interpretation of flow cytometry results, for example, is complicated because of the wealth of data generated and the lack of standardized analysis methods (Hammes and Egli, 2010; Van Nevel et al., 2017). Another drawback is the need to establish FCM baseline counts (i.e., those obtained during normal conditions) (Besmer et al., 2014). This necessitates widespread and long-term monitoring of the drinking water distribution system to determine flow cytometric cell counts under various conditions, and during different seasons (Besmer et al., 2014, 2016). Thus, application of flow cytometry for routine monitoring of the drinking water distribution system requires at least a few years of gathering data, in concert with other microbial monitoring methods, in order to accurately interpret results (Van Nevel et al., 2017). In addition, FCM is costly compared to other monitoring approaches, particularly due to the cost of the instrument.

Figure 8. Flow cytometry (FCM)

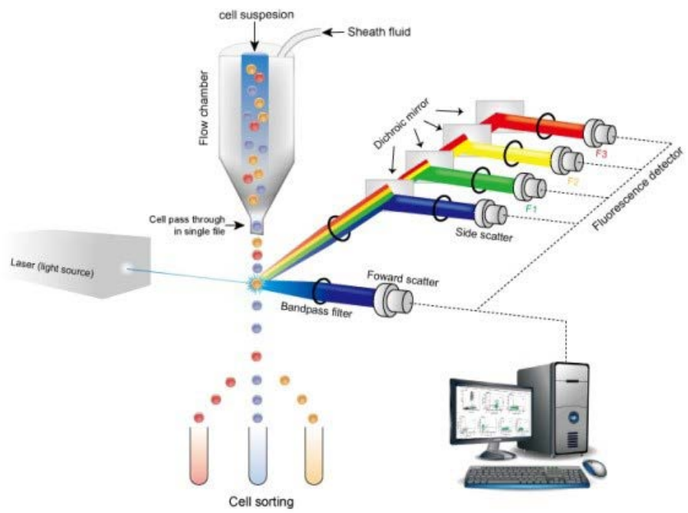

Table 4. Advantages and disadvantages of flow cytometry

Advantages	References
Able to measure changes in bacterial cell counts	Lautenschlager et al., 2013; Prest et al., 2013, 2016a,b,c; Nescerecka et al., 2014; Kennedy et al., 2021
Rapid (~15 minutes), accurate and quantitative	Van Nevel et al., 2017
Highly reproducible (e.g., relative standard deviations less than 2.5 for a single operator and machine)	Hammes et al., 2008; Wang et al., 2010; Prest et al., 2013; Kennedy et al., 2021
Able to determine viability by using nucleic acid-binding dyes	Ramseier et al., 2011
Amenable to automation which allows for high throughput (i.e., multi-well plate analysis feature permits analysis of up to 500 samples within a day)	Van Nevel et al., 2013
Online technology allows continuous FCM measurements for several subsequent weeks	Hammes et al., 2012; Brognaux et al., 2013; Besmer et al., 2014; Prest et al., 2013, 2016a,b,c
Detailed characterization of bacterial communities using FCM fingerprints	De Roy et al., 2012; Prest et al., 2013; Koch et al., 2014; Van Nevel et al., 2017; Favere et al., 2020
FCM fingerprints permit increased sensitivity in detecting small changes and shifts within the bacterial community, and consistent with 16S rRNA gene analysis	De Roy et al., 2012; Prest et al., 2013; Koch et al., 2014; Props et al., 2016
Disadvantages	**References**
Considerable requirements for equipment, user training, and data processing	Hammes and Egli, 2010
Subjective counting process (i.e., manual gating)	Hammes and Egli, 2010; De Roy et al., 2012; Aghaeepour et al., 2013; Prest et al., 2013
Does not discriminate between single cells or clumps (e.g., sloughed biofilm), potentially leading to undercounting	Shapiro, 2003; van der Kooij and van der Wielen, 2014
Standardized methods have not yet been developed for drinking water applications	Hammes and Egli, 2010; Lautenschlager et al., 2013; Prest et al., 2013

B.3.3.2 Molecular methods

A variety of molecular methods are available to assess microbial community diversity in drinking water distribution systems (Norton and LeChevallier 2000; Eichler et al. 2006; Henne et al. 2012; Pinto et al. 2012; Liu et al., 2013c, 2014, 2018; Prest et al., 2013, 2014, 2016a,b,c; Vierheilig et al., 2015; Ling et al., 2016; Van Nevel et al., 2017; Douterelo et al., 2018; Garner et al., 2021). These methods generally rely on detection, quantification and comparison of nucleic acid [Deoxyribonucleic acid (DNA) or Ribonucleic acid (RNA)]. The quantitative (q) polymerase chain reaction (PCR), also referred to as real-time PCR, is widely used for enumeration of gene targets within microorganisms present in the distribution system. This method involves processing water or biofilm samples in order to isolate DNA and/or RNA. In the case of biofilm, samples can be collected in a variety of ways, including: cut-outs of distribution pipes (LeChevallier et al., 1998; Wingender and Flemming, 2004, 2011), coupons inserted into pipes (Douterelo et al., 2016b), material mobilized into bulk water after flushing (Douterelo et al., 2014b, 2016a), household water meters (Hong et al., 2010; Ling et al., 2016), or coupons placed in a flow-through apparatus (see Section B.3.2.7).

Extracted nucleic material is then amplified using primers targeted at specific marker genes. In the case of bacteria and other prokaryotes, the 16s rRNA gene is the most widely used gene marker, whereas the18S rRNA and internal transcribed spacer genes are used for fungi and other eukaryotes (Bokulich and Mills, 2013; Bradley et al., 2016; Lan et al., 2016). Fluorescently-labelled oligonucleotide probes are also added. When these probes bind to double-stranded DNA, they fluorescence. Thus, as the target region is amplified, the emitted fluorescence is measured in real time, thereby allowing quantification of the PCR products.

Sequencing, whether it be marker gene regions or entire genomes, can provide useful information regarding the composition of microbial communities in the distribution system. A variety of next generation sequencing (NGS) technologies/platforms are available, allowing for rapid sequencing and thus, more timely and precise identification of microorganisms (Garner et al., 2021). While these and other molecular methods have several advantages, they also suffer from some significant shortcomings (Table 5), including their inability to distinguish viable from nonviable microorganisms.

Table 5. Advantages and disadvantages of molecular approaches

Advantages	**References**
Cultivation-independent	
Allow for additional (future) analyses by freezing extracted nucleic acid	Van Nevel et al., 2017
NGS technologies permit real-time sequencing	Tan et al., 2015; Goordial et al., 2017; Garner et al., 2021
Can be used for source tracking (i.e., determining origin of contamination)	Liu et al., 2018
Disadvantages	**References**
Inadequate detection limit (i.e., dependent on target gene and sequence length) and difficulties with viability assessment	Nocker et al., 2007, 2017
Time-intensive nucleic acid extraction	Nocker et al., 2007, 2017; Hwang et al., 2011, 2012; Salter et al., 2014
PCR amplification bias (i.e., choice of target and primers)	Nocker et al., 2007, 2017; Hwang et al., 2011, 2012; Salter et al., 2014
Varying assumptions and approaches to extraction, and fingerprint/sequence analysis and interpretation	
Costly and requires specialised molecular biology training	

B.3.3.3 Pipe autopsies and characterization of accumulated material

Information on the nature and quantity of material that accumulates in the distribution system can be obtained by collecting samples during pipe autopsies or when cleaning the distribution system (e.g., unidirectional flushing) (Carrière et al., 2005; Poças et al, 2013; Friedman et al., 2016). Sample analyses will depend on the source water and the study objectives. Areas to be studied can be selected based on consumer complaints, water quality concerns, disinfectant residual concentration, watermain characteristics (e.g., material, size, looped or dead-end), frequency of watermain breaks or where infrastructure is being replaced (Halton, 2001; Friedman et al., 2003; Meteer, 2018).

Pipe autopsies involve removing a section of watermain from the distribution system and characterizing the accumulated material (Halton, 2001; Muylwyk and MacDonald, 2001; Meteer, 2018). Meteer (2018) recommends performing successive scraping with a finger (protected with a silicon glove) and then with silicone, plastic and metal scrappers (in that order). Observations should be recorded and photos should be taken. Samples of the accumulated material should then be collected. Hydraulically-mobile deposits can be collected when conducting unidirectional flushing or another cleaning technique that involves a flow discharge. Hydrant nets are typically used to collect the hydraulically-mobile material at the point of flow discharge (Friedman et al., 2003).

The material collected can be characterized for a myriad of parameters as follows (Halton, 2001; Friedman et al., 2010a, 2016; Poças et al., 2013; Douterelo et al., 2014b; Hill et al., 2018; Meteer, 2018):

- physical composition (e.g., particle density and size, total suspended solids, volatile solids);
- chemical composition (e.g., metals, ions, nutrients);
- biological composition using common methods (e.g., ATP, HPC-R2A, total coliforms, iron-reducing bacteria, sulphur-reducing bacteria); and
- biological composition using advanced methods (e.g., viable bacteria using flow cytometry—see Section B.3.2.1, microbial community analysis – see Section B.3.4.2).

Carrière et al. (2005) recommends calculating the deposit accumulation rate to establish optimal cleaning frequencies and identify alternatives to limit the build-up of deposits in the distribution system (e.g., enhanced removal of material at the treatment facility, optimized coagulation/flocculation to minimize post-precipitation in the distribution system, corrosion control).

B.3.3.4 Water distribution system models

Small-scale physical models such as pipe rigs or pipe loops can be used to study how changes in water chemistry impact water quality and to evaluate mitigative measures (Health Canada, 2009b; Cantor, 2012, 2017, 2021; Friedman, 2014). These models generally provide insight into a myriad of factors related to biostability, including discolouration, scale formation and dissolution, microbiologically influenced corrosion and effects of operations.

Water distribution system computer models can aid in understanding changes in water quality, and in developing monitoring and sampling approaches (Skadsen et al., 2008). These computer models take into consideration the hydraulics of the distribution system, along with other characteristics to simulate distribution system dynamics (e.g., system pressures, pipe velocities, flow direction, water age, water blend ratios) (Kirmeyer et al., 2000; Powell et al., 2004; Friedman, 2020; Hatam et al., 2020). Computer models also allow water utilities to predict system behaviour under specified conditions or evaluate alternatives to address water quality issues (Powell et al., 2004; Speight and Khanal, 2009). A number of models are available, including the US Environmental Protection Agency (US EPA)s open-source drinking water distribution system model, referred to as EPANET (US EPA, 2018b). An EPANET module, referred to as EPANET-MSX (Multi-Species Extension), considers interactions between substances found in the bulk water and on the pipe walls (e.g. disinfectants, microorganisms). Hydraulic modeling is now relatively common (Shurtz et al., 2017) although it is critical that water utilities maintain a calibration program when using computer models (Clark et al., 2010). Water quality modeling remains complicated and challenging to apply (Speight, 2021).

Quantitative microbial risk assessment (QMRA) models can also be used in conjunction with hydraulic models to better understand the risks associated with deteriorating microbial water quality in distribution systems (Blokker et al., 2014, 2018). However, obtaining accurate input data to make results more meaningful remains challenging (Besner et al., 2011; Viñas et al., 2019).

B.4 MONITORING PROGRAM

B.4.1 Comprehensive monitoring program

It is important to recognize that distribution systems differ significantly in their design, size and complexity. No single monitoring program will meet the needs of all systems because of differences in spatial aspects (e.g., entry point, mid- and far-points, pressure zones), temporal aspects (e.g., diurnal or seasonal variations) and/or vulnerable sites (e.g., susceptible to intrusion, large or at-risk populations, areas with a high number of customer complaints) (Lindley and Buchberger, 2002; Hill et al., 2018). Therefore, water utilities should develop a monitoring program based on a system-specific assessment, and consider the cost and ease-of-use of monitoring methods, as well as the requirements of the responsible drinking water authority.

The system-specific assessment should establish monitoring objectives and confirm what needs to be monitored (AWWA, 2005). These elements will influence other considerations related to sample collection, location and frequency. For example, short duration events are unlikely to be captured using daily grab samples. Continuous water quality monitors increase the likelihood of detecting these events provided they are located in areas with temporal variation; storage facilities, in particular, can play an important role in affecting temporal water quality variability (Speight, 2010).

B.4.2 Sample collection

A variety of sample collection methods are available (see Table 6). Depending on the monitoring objectives, continuous online equipment or grab samples may be selected (EPA, 2018a).

Table 6. Available sample collection methods[a]

Parameter	Online/data logger	Grab—field	Grab—laboratory	Other
Bacterial indicators			X	
Disinfectant residual	X	X		
Turbidity	X	X		
Conductivity	X	X		
Pressure	X			
Temperature	X	X		
HPC			X	
cATP	X	X	X	
pH	X	X		
ORP	X	X		
Colour	X	X	X	
Nutrients	X	X	X	
Metals	X[b]	X[b]	X[b]	
Biofilm formation rate				X – flow-through apparatus and coupons
Corrosion rate				X – flow-through apparatus and metal coupons; linear polarization resistance using mild steel electrodes

[a] Excludes samples collected and/or analyzed using advanced methods.

[b] Depending on the monitoring objective, metals samples may be collected from distribution system locations (see Section B.4.4) or pipe rigs (Friedman, 2020), pipe loops (Health Canada, 2009b) or in-situ monitoring stations (Cantor et al., 2012; Cantor, 2021).

B.4.3 Sampling frequency

The sampling frequency ultimately depends on a system-specific assessment of the distribution system, including its size, complexity and temporal variability, in combination with any requirements established by the responsible drinking water authority. For example, if the intent is to quickly detect a water quality change, then sampling frequency should be high (Buchberger et al., 2003). Also, distribution system water temperatures of 15 °C may trigger an increase in sampling frequency from weekly to daily for some parameters (Health Canada, 2021b).

Guidance on sampling for bacterial indicators (i.e., *E. coli* and total coliforms) in the distribution system is available in Canada (Health Canada, 2020a,b) and globally (US EPA, 2013; WHO, 2011a, 2014). Water utilities should assess which parameters can be measured in the field or sampled when collecting bacterial indicator samples. To establish baseline conditions, sampling on a weekly (Cantor, 2017; Hill et al., 2018) or daily basis if practical (Friedman and Slabaugh, 2020) is recommended.

Event-based monitoring should also be conducted following hydraulic disturbances (e.g., watermain break, repair or flushing) or changes in water chemistry (e.g., changes to pH, disinfection residual type, source water type), as well as when discolouration of water has been reported (Friedman et al., 2016). Some samples should be collected from sites within the distribution system (such as hydrants or valves), as well as from drinking water taps in public or private buildings to help determine the cause of the event and at-the-tap concentrations.

Practical guidance on monitoring and evaluating distribution system water quality is available in Cantor (2018).

B.4.4 Sampling locations

Careful consideration should be given to identifying locations within the drinking water distribution system where the risk of water quality deterioration is likely highest. This requires an understanding of the distribution system through a detailed description of the location of major transmission components and distribution mains. Distribution system layout details, such as the location of storage facilities, pumps, valves, meters and consumer connections, need to be considered. Additional system attributes, including pipe material, age and breakage records, are important to capture when determining where to sample. Historical water quality data are also integral to informing selection of monitoring locations (e.g., sites where contamination previously occurred). It is also important to consider system hydraulics

(e.g., average water age compared to dead-ends and high water age). The types of buildings (e.g., schools, hospitals) supplied by the distribution system should also be considered, as they represent a higher number of potential exposures.

In addition to distribution system characteristics and water quality data, selection of monitoring locations will depend on the requirements of the responsible drinking water authority. Thus, the responsible drinking water authority should be consulted when identifying sampling locations.

In general, the entry point to the distribution system and points near dead-end zones and poor hydraulics (i.e., high water age) should be targeted for monitoring (Islam et al., 2015; Cantor, 2017). For metals, areas with variable turbidity (e.g., particulate solids in the water) or conductivity (e.g., dissolved solids in the water) should be targeted. In the absence of turbidity and conductivity data, sites where bacterial indicator samples are collected can be used in the interim. Once possible sampling locations have been identified, it is important to ensure that they are spatially representative (Vital et al., 2012; Nescerecka et al., 2014; Hill et al., 2018). Sample locations can be refined as water quality data is collected and trends are assessed.

B.4.5 Data analyses and response

Data generated should be tracked to evaluate trends and variability. This will allow systems to determine baseline water quality conditions (e.g., normal variations not requiring action), and thus, identify if, and how, the biological stability is changing in the distribution system. Water utilities can then establish water quality goals for the distribution system. System-specific alert and action limits should also be established to trigger preventive or corrective actions (AWWA, 2005; Cantor and Cantor, 2009). Standard operating procedures should clearly outline what actions are necessary to avoid water quality deterioration (i.e., preventive action) and to address a potential adverse water quality condition (i.e., corrective action). The objective of tiered response protocols is to avoid the need for emergency measures which are generally much more complex and labour-intensive (AWWA, 2005). If water quality goals are not met, the system-specific preventive or corrective actions should be taken (Ballantyne and Meteer, 2018).

More detailed information on water quality monitoring data management and analysis is available elsewhere (AwwaRF, 2002; Cantor and Cantor, 2009; AWWA, 2017a; Cantor 2018).

B.5 MANAGEMENT STRATEGIES

The drinking water distribution system is the last protective barrier before the consumers' tap. A well-maintained and operated distribution system is a critical component of providing safe drinking water. Although drinking water distribution systems can vary considerably, they face common challenges, including water quality deterioration (see Section B.2). In order to ensure delivery of safe drinking water to consumers, the causes of this deterioration need to be understood. It is recommended that water utilities develop a distribution system monitoring plan to identify sources of contamination and/or causes of microbial (re)growth.

Monitoring results inform the selection of appropriate management strategies. Some strategies are discussed below; water utilities are responsible to identify and manage the full range of risks that may apply to their system(s). Comprehensive reviews can be found elsewhere (NRC, 2006; Kirmeyer et al., 2014; Mosse and Murray, 2015; Cantor, 2017, 2018).

B.5.1 Water entering the distribution system

Water utilities should be aware of how source water quality and treatment processes impact the biological stability of water entering the distribution system. For example, groundwater typically has lower cell counts and less organic nutrients compared to surface water (Najm et al., 2000; Prest et al., 2016b). However, groundwater can have higher concentrations of inorganic nutrients (e.g., iron, manganese, nitrogen or sulphur) (AWWA, 2011) and sediment may accumulate in the distribution system, storage facilities, etc. (Lotimer, 2012). Also, anaerobic groundwater can have high biofilm formation rates (i.e., up 80 pg ATP/cm^2-d) (van Lieverloo et al., 2012) likely due to high concentrations of methane, iron, ammonium or manganese (de Vet, 2011). Surface and subsurface sources should be characterized with regard to nutrient concentrations (Cantor, 2017).

Treatment processes can also significantly impact the quality of water entering the distribution system (AWWA, 2011). For example, oxidation processes produce biodegradable nutrients upon reaction with organic matter (Alarcon-Herrera et al., 1993; Bursill, 2001; Reckhow et al., 2007). Thus, biologically active filtration may be necessary to stabilize treated water (GLUMRB, 2012). In some European countries, the approach taken to achieve biological stability is to produce drinking water with an assimilable organic carbon of <10 µg/L to control or limit microbial activity in the absence of a disinfectant residual (van der Kooij, 2000; Smeets et al., 2009; Lautenschlager et al., 2013). In North America, minimum disinfectant residuals are typically recommended to effectively control (re)growth in the distribution system (LeChevallier et al., 1996; LeChevallier and Au, 2004) (see Section B.5.2).

In addition, the pH selected for treated water should consider chemically-influenced processes in the distribution system (i.e., corrosion, adsorption/desorption). To maintain biological stability, pH variability should be maintained within ±0.2 units throughout the distribution system (Muylwyk and MacDonald, 2001; Friedman et al., 2010a; Health Canada, 2015).

B.5.2 Disinfectant residual

It is important to ensure the disinfectant residual leaving the treatment facility is stable otherwise it may be difficult to maintain a residual throughout the distribution system (Alexander et al, 2019; US EPA, 2019). A "hold study" is a simple and cost-effective way to assess how long a disinfectant residual can be effectively maintained in the distribution system. The study involves collecting samples, "holding" them for a duration representative of the system retention time and measuring disinfectant residual decay. It can be conducted for both cold (<10 °C) and warm (>10 °C) water conditions to assess the impacts of temperature. Study findings identify where water utilities should focus their efforts (e.g., the treatment facility or the distribution system). An example of a treatment change is to improve organic carbon removal, which has multiple benefits—it reduces the disinfectant demand thereby increasing residual stability and reduces the potential for biofilm formation in the distribution system which in turn increases residual persistence (Chandy and Angles, 2001). Practical guidance is available to help water utilities carry out hold studies (Alexander et al. 2019; US EPA, 2019). Other approaches to maintain an effective disinfectant residual in the distribution system include managing water age (see Sections B.5.3 and B.5.4) and reducing the disinfectant demand associated with loose deposits (see Section B.5.5).

B.5.3 Storage facilities

Storage facilities are important infrastructure assets to maintain distribution system pressure and supply peak water demands. However, they can cause water quality deterioration if they are not properly operated and maintained (see Section B.1). Stagnation and excessive retention time can result in thermal stratification, loss of disinfectant residual, and/or (re)growth (US EPA, 2002b; Delahaye et al., 2003). For those systems that chloraminate, nitrification is often associated with storage facilities (US EPA, 2002b; Baribeau et al., 2005). Storage facility sediments have also been shown to harbour OPPPs such as *Legionella* spp. and *Mycobacterium* spp. (Lu et al., 2015; Qin et al., 2017).

In light of the risks associated with storage facilities, guidance and/or design standards to avoid stagnation and minimize retention times are available from provincial/territorial jurisdictions or industry associations (e.g., AWWA). It is also important to establish a unique monitoring program for each storage facility (e.g., operational data, sediment and biofilm sampling) to determine:

- a turnover rate to maintain target disinfectant residual concentrations and manage water age for temperatures <15 °C and >15 °C; and
- an inspection, cleaning and maintenance schedule to detect potential entry points for contamination and remove accumulated material.

Practical guidance to manage the risks associated with storage facilities is available (Kirmeyer et al., 1999; Martel et al., 2002; US EPA, 2002b). Information regarding the disinfection of storage facilities and field dechlorination is available in ANSI/AWWA (2019) and (2018), respectively.

B.5.4 Water age and hydraulic integrity

To manage water age, water utilities should aim to minimize the retention time in watermains and storage facilities (see Section B.5.3). To reduce water age in watermains, careful system design is necessary. Oversized or dead-end watermains can lead to excessive water age hence procedures should be in place to manage water quality deterioration (Kirmeyer et al., 2000; AWWA, 2011). For example, post hydrants can be installed to flush dead-end watermains (Locco and Alberton, 2021). Special precautions may apply for long transmission mains that connect two or more communities (e.g., regional systems, rural pipelines). The responsible drinking water authority should be contacted to confirm applicable requirements.

Water utilities should also have strategies that aim to minimize: 1) pressure fluctuations (i.e., transients); 2) rapid and/or extreme fluctuations in flow velocities; and 3) the frequency of flow reversals. These types of activities can cause watermain breaks (Rathnayaka et al., 2016) or stir up and entrain the material that has accumulated in the distribution system. The latter can result in discoloured water events (Prince et al., 2003; AWWA, 2011), as well as at-the-tap concentrations that exceed maximum allowable concentrations (Friedman et al., 2016). Intelligent control systems[1] can mitigate the effects of pressure transients (e.g., slow pump start/stop); this, in turn, minimizes physical and hydraulic disturbances (Blake, 2019; Steger and Pierce, 2019). Advances in high-speed pressure measuring equipment (e.g., multiple readings per second) has also facilitated the implementation of programs to reduce water leakage and watermain breaks (Chapman and Ziemann, 2019; Sutherns, 2019; Ginn and Smither, 2020; Hamilton and Nikolica, 2021). Coordination with the agencies that conduct fire flow testing can also prevent hydraulic fluctuations (AWWA, 2011).

B.5.5 Watermain cleaning

Proactive watermain cleaning can minimize the risks associated with the material that has accumulated in the distribution system. A variety of pipe cleaning strategies, aimed at removing biofilm, loose deposits and sediment, are available, including unidirectional flushing (Ellison, 2003; Bellas and Tassou, 2005, Quarini et al., 2010, Vreeburg et al., 2010; Dang et al., 2014; Friedman et al., 2016; Liu et al., 2017). Cantor (2017) stressed the importance of removing accumulated material as this measure was better correlated with lower lead and copper releases than traditional corrosion control in 12 municipal and non-municipal water systems using ground and surface water. A survey of 41 full-scale systems found the most common cleaning interval was annually regardless of the type of residual disinfectant (Baribeau et al., 2005). An optimal cleaning frequency can be determined from the deposit accumulation rate (see Section B.6) (Carrière et al., 2005).

Caution is needed when using flushing. It is important that water utilities identify and implement the most appropriate flushing technique to avoid disturbing and releasing legacy deposits into the bulk water. Improper flushing techniques can stir up and potentially spread contaminants around the flushed area or deeper into the distribution system, thus increasing public health risk. The following conditions can disturb legacy deposits: excessive flushing rate or velocity; insufficient flushing rate or velocity; lack of directional control; and, inadequate flush duration (Hill et al., 2018). Automatic flushing stations are recommended if the goal is to turnover bulk water in an area due to water age or poor circulation (Hill et al., 2018).

B.5.6 Infrastructure integrity

Infrastructure integrity relates to the ability of the distribution system to act as a physical barrier to contamination (NRC, 2006). Contamination that enters the distribution system from external sources such as cross-connections, watermain breaks or leaks can compromise water quality and lead to illness (see Section B.1). Thus, it is incumbent on water utilities to have appropriate programs and/or procedures to manage these risks as briefly described below.

The need for backflow prevention and cross-connection is well established and devices are available to mitigate this risk (NRC, 2006; AWWA, 2015b). Data indicates that water utilities with low pressures experience a greater number of backflow incidents (Lee et al., 2003). Schneider et al. (2016) determined the average monthly backflow occurrence rate to be 1.6% using reverse flow sensing meters. Areas vulnerable to backflow can be identified using water distribution system hydraulic modeling (Lindley and Buchberger, 2002; Lee et al., 2003; Schneider et al., 2016). Guidance is available to help water utilities develop a backflow prevention and cross-connection program (AWWA, 2015b).

With regards to watermain breaks, there is increasing awareness that improved response procedures are needed to protect public health (Besner et al., 2008; Kirmeyer et al., 2014; Hatam et al., 2020). Kirmeyer et al. (2014) assessed the risk of microbial contamination and tailored response procedures (e.g., boil water advisory, microbiological sampling) based on whether positive pressure could be maintained. Hatam et al. (2020) found that large volume sampling for bacterial indicators (as part of response procedures) could be appropriate at times. In addition, strict hygiene should be practiced during all watermain construction, repair or maintenance to ensure drinking water is transported to the consumer with minimum loss of quality (Kirmeyer et al., 2001, 2014). Information regarding the disinfection of watermains and field dechlorination is available in ANSI/AWWA (2014) and (2018), respectively.

1 A combination of interconnected sensors, instruments and other devices, database structure and data analytics that provide real-time status and control of operations.

A proactive leak detection program can achieve multiple benefits—less frequent leaks and watermain breaks, reduced leakage and risk of contamination, as well as asset life extension (Kachani et al., 2020). Guidance is available to help water utilities develop a program to control water loss (AWWA, 2016). Advances in high-speed pressure measuring equipment and machine learning have also improved the ability to predict watermain failures (Fitchett et a., 2020; Sutherns, 2020). "Smart" water meters can also provide flow direction, pressure and temperature data.

B.5.7 Consumer complaints

Water utilities should have programs to capture, track, analyze and resolve consumer complaints (Friedman et al., 2010b). Consumer complaints of colour, or unpleasant taste and odour, can serve as an important indicator of water quality deterioration in the distribution system (Hrudey and Hrudey, 2014). Consumers should be advised that discoloured water should not be considered safe to consume until it has been tested for metals and confirmed to be safe (Friedman et al., 2016). During watermain breaks or flushing activities, water utilities should have procedures in place to notify residents of the potential risks associated with discoloured water (i.e., elevated metals concentrations). Consumers should be advised to minimize water use to avoid sediment entering the service line. After the work is completed, homeowners should be advised to run the cold water tap in the lowest level of their residence for 5–10 minutes to eliminate any discoloured water that may have entered (Locco et al., 2018). Building owners/managers may require other precautions (see Section B.7).

B.6 WATER QUALITY TARGETS

Water utilities should aim to maintain biologically stable water quality conditions by considering the following:

- microbially-influenced processes (Cantor, 2017);
- chemically-influenced processes such as corrosion or adsorption/desorption from materials/deposits in the distribution system (AWWA, 2011);
- physical/hydraulic changes (Besner et al., 2010; Friedman et al., 2010a,b, 2016; Cantor, 2017, 2018; Hill et al., 2018).

To achieve this, it is important that water utilities have a comprehensive monitoring program. Metrics for select parameters are summarized in Table 7. Table 7 is provided as guidance only based on the literature review that was completed to develop this document. As a result, some parameters discussed in Section B.3 may not appear in the table.

Water utilities are responsible to ensure that the distribution system is characterized and that an appropriate management plan is developed to achieve water quality goals. Water utilities may choose to use these metrics as initial water quality targets until they have sufficient data to establish system-specific values.

Table 7. Metrics for select parameters

Parameter	Units	Systems using chlorination	Systems using chloramination	References
Disinfectant residual	mg/L	≥ 1.0 and minimize variability	≥ 1.8 and minimize variability	Gagnon et al., 2008 Gillespie et al., 2014 Rand et al., 2014 LeChevallier et a., 2015a,b
Temperature[a]	°C	15 – biofilm formation rate 20 – corrosion rate 20 – disinfectant variability	15 – biofilm formation rate 20 – corrosion rate 22 – disinfectant variability	LeChevallier et a., 2015a,b
cATP	pg/mL	<1 good control 1–10 preventive action >10 corrective action	<1 good control 1–10 preventive action >10 corrective action	McIlwain, 2020
pH	No units	Minimum 7.0 and maintain variability within ±0.2	Minimum 7.0 and maintain variability within ±0.2	Muylwyk and MacDonald, 2001 Friedman et al., 2010a Health Canada, 2015
Oxidation reduction potential	mV	>400	>400	Friedman, 2020
Dissolved organic carbon[b]	mg/L	<1.8	<1.8	LeChevallier et a., 2015a,b
Biofilm formation rate[c]	pg/mm^2-d	0.090	0.017	LeChevallier et a., 2015a,b
Deposit accumulation rate	g/m/yr	<1 – flush as needed 1–10 – flush annually >10 – corrective action	<1 – flush as needed 1–10 – flush annually >10 – corrective action	Carrière et al., 2005

[a] Threshold values at which the noted aspect (e.g., biofilm formation rate) has been observed to increase.

[b] Dissolved organic carbon is a measure of nutrients. Systems that chloraminate require additional targets (e.g., free ammonia).

[c] Measured by adenosine triphosphate (ATP) accumulated on mild steel coupons.

B.7 MICROBIAL RISK IN BUILDINGS/PREMISE PLUMBING

Premise plumbing refers to the portion of drinking water distribution system beyond the property line and in schools, hospitals, public and private housing, offices and other buildings (NRC, 2006; US EPA, 2016b). Water use in buildings includes drinking, food preparation, washing and showering, cooling systems and features (e.g., ornamental fountains).

Water quality can diminish significantly in building premise plumbing and is influenced by the same factors as those in drinking water distribution systems (see Section B.2). However, building (premise) plumbing systems face some additional challenges, including: 1) longer residence times (i.e., increased water stagnation); 2) increased water temperatures; 3) use of a variety of plumbing components and materials; 4) small pipe diameters; and 5) use of water treatment devices, such as reverse osmosis systems, that can increase corrosion. Long residence times in premise plumbing have been linked to significantly higher concentrations of microbial populations, and shifts in microbial community composition (Pepper et al., 2004; Lautenschlager et al., 2010; Manuel et al., 2010; Lipphaus et al., 2014; Bédard et al, 2018). Higher water temperatures, due to pipes being installed in heated rooms or near heat sources, promote microbial (re)growth (Lautenschlager et al., 2010; Lipphaus et al., 2014). (Re) growth is also influenced through interaction with various plumbing materials, such as plastic tubing and rubber fittings, which have considerable microbial growth promotion potential (Bucheli-Witschel et al., 2012). Smaller pipe diameters result in increased contact between microorganisms and pipes, leading to enhanced pipe material impacts (see Section B.2.3), including biofilm formation and lowered disinfectant residual concentrations (Servais et al., 1992; Rossman et al., 1994; Prévost et al., 1998). As noted earlier (see Section B.2.1), these biofilms can harbour pathogens, including OPPPs. Premise plumbing systems can dramatically enhance the growth of *Legionella* spp. and other OPPPs, such as *Pseudomonas aeruginosa* and non-tuberculous Mycobacteria, and are a significant public health concern, particularly, in hospitals (WHO, 2011b).

Premise plumbing can also impact water quality in the distribution system. The main mechanism by which microbial contamination can enter the drinking water distribution system from building premise plumbing is through backflow, either by back-siphonage or back pressure (WHO, 2011b, 2014). Thus, it is important that appropriate backflow and cross-connection control programs are in place (AWWA, 2017a).

Given the unique water quality challenges present in buildings, additional management strategies are required. It is important to note that water utilities are not generally responsible for water quality from the property line to individual points of use in buildings. Building owners or managers must monitor and manage their water systems in order to ensure safe water at the consumers tap. Management of water quality in buildings begins with accurate and up-to-date maps of building water systems and labeling of pipework, particularly in large buildings. These are important tools to help avoid cross-connections, and identify zones were water can stagnate.

Although it is beyond the scope of this document to specify where, when and how to routinely monitor premise plumbing, some guiding principles include:

- Environmental sampling for bacteria should not occur in isolation, but as a part of a comprehensive building water management program.
- Sampling plans are unique to each building and should be based on building characteristics (e.g., size, age, layout, population served) and historical water quality data (e.g., trend analysis of previous bacterial test results, water quality parameters such as disinfectant residual and temperature).
- Water quality can vary between floors, outlets and hot and cold water taps; sites that may produce water aerosols should be considered for sampling.
- A sampling approach can be adapted based on trends and system changes.
- If indicators of potential microbial growth or other issues are detected (e.g., discoloured water, unpleasant tastes or odours and slimes in water-using devices), corrective actions such as flushing or disinfection may be needed in the building water system.

Detailed information on managing water safety in buildings is available elsewhere (WHO, 2011b; Health Canada, 2013; Public Works and Government Services Canada, 2013; ASHRAE, 2000, 2015, 2018).

B.8 INTERNATIONAL CONSIDERATIONS

Other national and international organizations have drinking water guidance, guidelines, or standards related to monitoring water quality and biological stability in the distribution system. Variations in these can be attributed to when the assessments were completed or to differing policies and approaches. The WHO advocates a water safety plan approach that includes an operational monitoring program in the distribution system and in buildings. The WHO also suggests optimized natural organic matter removal as a means to minimize biofilm growth in the distribution system. In Australia, operational and drinking water quality monitoring parameters are defined for assessing the potential for stagnation, biofilm formation, and ingress of contamination in the distribution system. The United States US EPAs Revised Total Coliform Rule establishes routine sampling at sites throughout the distribution system, with requirements to "find and fix" sanitary defects in the distribution system. The US EPA also provides guidance on distribution system water quality monitoring in the form of various white papers and reports. The European Unions Drinking Water Directive establishes a minimum frequency of sampling in the distribution system based on the volume of water distributed or produced each day within a supply zone; and defines a series of "check monitoring" parameters.

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APPENDIX A
LIST OF ACRONYMS

ASTM	ASTM International
ATP	Adenosine triphosphate
AWWA	American Water Works Association
BOM	Biodegradable organic matter
cATP	Cellular adenosine triphosphate
DNA	Deoxyribonucleic acid
E. coli	Escherichia coli
EPS	Extracellular polymeric substances
FCM	Flow cytometry
HPC	Hetrotrophic plate count
NGS	Next Generation Sequencing
NRC	National Research Council
OPPP	Opportunistic premise plumbing pathogens
ORP	Oxidation-reduction potential
PCR	Polymerase chain reaction
PI	Propidium iodide
PVC	Polyvinyl chloride
q	quantitative
QMRA	Quantitative microbial risk assessment
RNA	Ribonucleic acid
rRNA	Ribosomal ribonucleic acid
US	United States
US CDC	United States Centers for Disease Control and Prevention
US EPA	United States Environmental Protection Agency
WHO	World Health Organization

APPENDIX B
SELECT INFECTIOUS DISEASE OUTBREAKS RELATED TO THE DRINKING WATER DISTRIBUTION SYSTEM[a]

Date	Location, country	Estimated (confirmed) cases	Population served	Causative agent	Possible causes
Oct 1980[b]	Grums and Vålberg, Vårmland, Sweden	2,000 (221)	~15,000	*Campylobacter jejuni*	Cross-connections with factory system; untreated river water was introduced into the distribution system
Dec 1989-Jan 1990[b]	Cabool, Missouri, USA	243 4 deaths	~2,100	*E. coli* O157:H7	Sewage infiltration during watermains repair and/or water meter replacements
Nov-Dec 1993[b]	Gideon, Missouri, USA	650 (31), 7 deaths	~1,100	*Salmonella typhimirium*	Suspected contamination of storage tanks by bird feces; flushing of system drew tank water into service
1995	Freuchie, Fife, Scotland	633	1,100	*E. coli* O157:H7	Cross-connection with vegetable processing company; untreated creek water was introduced into the distribution system
2000	Strasbourg, France	53	60,000	Unknown (gastroenteritis symptoms)	Watermain repair in the network
2000	Bari, Italy	344	1,000	Norovirus	Break in pipeline public supply connecting to resort tank
2000	Belfast, UK	117	Unknown	*Cryptosporidium*	Seepage of raw sewage from a septic tank into the water distribution system
2000	South Wales, UK	281	Unknown	*Campylobacter*	Seepage of surface water contaminated by agricultural waste following heavy rainfall into drinking water reservoir

Date	Location, country	Estimated (confirmed) cases	Population served	Causative agent	Possible causes
2000	Ohio, USA	29	Unknown	*E. coli*	Possible back-siphonage from an animal barn
2001	Darcy le Fort, France	563	1,100	*Cryptosporidium*, rotavirus, *Campylobacter* and *E. coli*	Sewage contamination occurred in the distribution network upstream to the city
2001	Lleida, Spain	96	293	Norovirus	Contamination of reservoir due to lack of maintenance and structural deficiencies
2001	Utrecht, The Netherlands	37	1,866	Norovirus	Drinking water system connected to grey water system in maintenance work; cross-connection not removed
2001	Belfast, UK	230	Unknown	*Cryptosporidium*	Entry of wastewater into the drinking water supply due to a blocked drain
2002	Vicenza, Italy	670	3,006	Unknown (gastrointestinal symptoms)	Broken sewage pipe allowed untreated water from the river to enter the city aqueduct
2002	Switzerland	125	Unknown	Norovirus	Fecal contamination from sewage leakage
2004	Ohio, USA	1,450	Unknown	*Campylobacter*, norovirus and *Giardia*	Unspecified distribution system deficiency related with untreated groundwater
2007	Køge, Denmark	140	5,802	Campylobacter, E. coli and norovirus	Technical and human error at sewage treatment plant allowed partially filtered wastewater to enter the distribution system
2007	Nokia, Finland	8,453 2 deaths	30,016	Multiple pathogens Norovirus, Campylobacter and Giardia	Cross-connection leading to drinking water network contaminated by treated sewage effluent
2008	Zurich (Adliswil), Switzerland	126	2,000	Multiple pathogens *Campylobacter* and norovirus	Cross-connection leading to input of highly pressurized washwater from sewage plant into the distribution system
2008	Northampton, UK	>422	250,000	*Cryptosporidium*	Dead rabbit found in a storage tank
2008	Alamosa, Colorado, USA	1,300, 1 death	Unknown	*Salmonella*	Likely animal contamination of a storage tank
2009	Utah, USA	8	Unknown	*Giardia*	Cross-connection between potable and non-potable water sources resulting in backflow
2010	Køge, Denmark	409	20,000	*Campylobacter*	Contamination of central water supply system by unknown mechanism
2010	Öland, Sweden	200	Unknown	Norovirus	Untreated water from well in the distribution system
2010	Saratoga Springs, Utah, USA	628	Unknown	*Campylobacter*	Cross-connection between potable and non-potable water sources resulting in backflow
2012	Kilkis, Greece	79	1,538	Norovirus	Heavy snowfall and runoff, low temperatures and 15 days without use of schools public water supply increased microbial load
2012	Kalundborg, Denmark	187	Unknown	Norovirus	Contamination from sewage pipe, due to fall in pressure, during repairs
2012	Vuorela, Finland	800	2,931	Sapovirus and *E. coli*	Main pipe accidently broken during road construction; flushing after breakage repair proved insufficient and storage reservoir was contaminated
2013	Guipuzko, Spain	238	650	Norovirus and rotavirus	Cross-connection between drinking water supplies and industrial water taken from a river

[a] Adapted from Moreira and Bondelind, 2017.

[b] Hrudey and Hrudey, 2004.