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Distribution System Indicators of Drinking Water Quality

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Background and Disclaimer

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

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

Additional Information

The paper is available at the TCR web site at:

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

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

Distribution System Indicators of Drinking Water Quality
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1 Introduction

As discussed in the “TCR and Distribution System Issue Papers Overview,” EPA plans to assess the effectiveness of the current TCR and determine what alternative and/or additional monitoring strategies are available, and to consider revisions to the TCR with new requirements for ensuring the integrity of the distribution system. Part of this assessment entails reviewing available indicators of distribution system water quality and determining whether a potential indicator can adequately identify the failure of barriers that protect against waterborne disease.

This paper compiles available information on indicators of drinking water quality within potable water distribution systems. The indicators include microbial and non-microbial parameters for which sample collection and analyses could be performed to identify existing or potential problems, as well as other methods or tools that may similarly function as problem indicators. Distribution-related problems for which indicators are evaluated are based on the priority issues identified for the Distribution System White Papers developed for the Total Coliform Review potential revisions (USEPA, 2006). For the purposes of this paper, the distribution system-related problems for which indicators might be used were divided into three categories that represent the range or degree of severity associated with problem outcomes including:

1) Indicators of Pathways that Breach Distribution System Integrity
2) Indicators of Distribution System Contamination
3) Indicators of Public Health Risk

The descriptions of each indicator were compiled by reviewing the primary literature available in online databases, such as Medline and Biological abstracts; resource materials from reference books, technical reports, and technical conference proceedings; and additional documents previously prepared for the U.S. Environmental Protection Agency (EPA).

Many or all of the indicators addressed herein may be useful for purposes other than distribution system assessment, including the identification of water treatment effectiveness or source water treatment needs. This paper focuses only on distribution system applications. As such, topics beyond the scope of this paper include the following: indicator applications for environmental monitoring of groundwater and surface waters, water quality issues related to recreational exposure to water, and treatment monitoring at source water treatment facilities or at the point of entry of the treated water to the distribution system. On some occasions, however, if information is not available regarding potential use of an indicator in the distribution system, then the performance of an indicator in source water or during treatment may be discussed. The discussion includes both regulated and unregulated indicators.

2 Background

Drinking water monitoring based upon tests for coliform bacteria as indicators of fecal contamination originated approximately 100 years ago (Cox, 1997). At that time, most waterborne disease outbreaks were caused by pathogenic organisms and could be clearly traced to fecal contamination of drinking water. The prevention of gastrointestinal illness from drinking water exposure meant keeping human fecal material out of water, and the best available technology for detecting fecal contamination was to monitor drinking water for the presence of coliform bacteria.

Today, water is treated and piped through elaborate distribution systems. The age and complexity of distribution systems, coupled with the increased availability and use of chemicals, has increased the likelihood for contamination events and waterborne disease not related to source water treatment deficiencies. There is also endemic disease that is suspected to occur due to contamination of distribution systems (Payment et al., 1991). Monitoring water for indicators and for other conditions that may provide information on distribution system deficiencies and integrity problems is an important tool for protecting the public health.

2.1 Organization of the Paper

Section 3 discusses key definitions. Section 4 provides the rationale for using indicators and an overview of the desired characteristics of an ideal indicator. Section 5 discusses distribution system problems for which indicators could potentially be used. These problems serve as the basis for the information compiled for each indicator and how indicators are subsequently compared.

Section 6 lists all of the indicators addressed in this paper and is organized into types of indicators in terms of Microbial, Chemical, or Other for convenience. For each indicator the discussion addresses potential applications of the indicator in terms of the distribution system problems outlined in section 5. This includes application as: an indicator of pathways that breach distribution system integrity; an indicator of distribution system contamination; and an indicator of public health outcome. Many indicators could potentially be used in all three problem categories, to differing degrees.

Section 7 presents the summary table of indicators grouped by the distribution system problems that they can potentially help identify. The usefulness of each indicator in the various applications has been designated as either “strong”, “weak”, or “not applicable”. The rationale used for selecting these designations is provided in Section 7.

3 Definitions

3.1 Distribution System

Within the context of this paper, a distribution system is defined as a system of conveyances that distributes potable water. All pipes, storage tanks, pipe laterals, and appurtenances that comprise the delivery system are included in this definition. Appurtenances owned and operated by private customers, such as service lines and plumbing components, that are typically not considered the responsibility of the public water system purveyor are also considered in this definition because they are physically attached to the distribution system and could potentially be a source of contamination, through, for example, backflow or leaching of contaminants from service lines. These and similar events may affect the water quality under the purveyor's jurisdiction. However this paper does not consider indicators that specifically identify problems in household plumbing.

3.2 Indicator

An "indicator" is a parameter that can be measured and used as a surrogate for another parameter or condition which either cannot be directly measured or is difficult to directly measure. Indicators are used in many contexts and the definition for an indicator may vary based on its use. By definition a contaminant cannot be an indicator of itself. In the context of distribution system assessment, an indicator is a surrogate that is used to demonstrate or predict vulnerability to: pathways that breach distribution system integrity; distribution system contamination; or the potential for public health risk outcomes.

4 Rationale for Use of Indicators

4.1 Why Not Monitor Directly for Contaminants?

Many contaminants have been identified as causes of waterborne disease outbreaks from drinking water exposures. These contaminants can enter the distribution system from multiple pathways, as presented in Section 5. Waterborne pathogens are biologically diverse, including bacteria, viruses, and protozoa. While methods for the detection of some pathogens and microorganisms have been developed, some of the methods are extremely labor intensive, require long incubation periods, require special reagents, or are very expensive. Some pathogens and viruses have never been successfully propagated in the laboratory. Even where the methods are available, few laboratories have the expertise and the facilities to isolate and identify pathogens capable of causing waterborne diseases. In addition, monitoring directly for a single pathogen will only provide information for that specific pathogen and may not provide information about other potential contaminants, unless the degree of co-occurrence of the organisms can be determined. The resources and technology needed to monitor for all potential pathogens is not available for most water systems.

Similarly, numerous chemical compounds can contaminate distribution systems. Timely monitoring for each and every chemical compound that could be present in the distribution system is simply not feasible for most water systems given technical and resource constraints.

Under certain circumstances, the use of an indicator as a surrogate for the direct measurement of multiple pathogens or compounds, or as the first-level screening tool to better focus on specific pathogens, can be an effective and feasible approach.

4.2 What Is an Ideal Indicator?

The characteristics of an ideal indicator vary based on the specific context or situation that an indicator is measuring. For distribution system water quality and infrastructure condition, a broad definition of the ideal indicator is not available that covers both microbial and chemical contamination. However, considerable literature is available on the characteristics of an ideal indicator for one type of distribution system contamination – fecal contamination. The following discussion focuses on indicator attributes for only fecal contamination, but the concepts could also be applied across other types of contamination or conditions.

The characteristics of the "ideal indicator" for fecal contamination were proposed by several investigators beginning with Bonde (1962 and 1966) and followed by Scarpino (1971), Dutka (1973), Cabelli (1977), Barrow (1981), and the NRC (2002). These characteristics are described in Exhibit 1.

Exhibit 1 Characteristics of the Ideal Microbial Indicator of Fecal Contamination

Characteristic	**Bonde 1966**	**Scarpino 1971**	**Dutka 1973**	**Cabelli 1977**	**Barrow 1981**	**NRC 2002**
Be present when and where pathogens are present	X	X	X	X		
Be unable to replicate and grow in the environment	X	X	X		X	
Be more resistant to disinfection than pathogens	X		X	X	X	X
Be easy to isolate and enumerate	X	X	X	X	X	
Be applicable to all types of water		X				
Not be subject to antibiosis	X					
Be absent from sources other than sewage or be exclusively associated with sewage				X	X	
Occur in greater numbers than pathogens	X					X
Density of indicator should have a direct relationship to degree of fecal contamination		X				
Indicator density should correlate with health hazard from a given type of pollution				X		
Correlated to health risk						X
Similar (or greater) survival compared to pathogens						X
Similar (or greater) transport compared to pathogens						X
Specific to a fecal source or quantifiable as to source of origin						X
Desirable Attributes of Indicator Methods						
Specificity to desired target organism						X
Broad applicability						X
Precision						X
Adequate sensitivity						X
Length of time to get results						X
Quantifiable						X
Measures viability or infectivity						X
Logistical feasibility						X

Adapted from Dufour, 1984.

5 Distribution System Problems

The distribution system problems discussed in Section 5 are grouped into the following sequential focus areas:

1) Pathways that Breach Distribution System Integrity

- Main Breaks, Repairs and Installation
- Operation and Maintenance Deficiencies
- Cross-connections and Backflow
- Intrusion
- Permeation
- Finished Covered Storage Tank Deficiencies
- Biofilms
- Corrosion and Leaching

2) Distribution System Contamination

- Fecal Contamination
- Toxic or carcinogenic contamination

3) Public Health Risk
- Waterborne disease Outbreaks and Endemic Illness

By evaluating indicators in a sequential manner (e.g., it is possible to have a breach in distribution system integrity but not cause contamination, and it is also possible to have a contamination event, but not cause a waterborne disease), the indicators can be considered with regard to their effectiveness as predictive and/or forensic tools. The pathways that breach distribution system integrity can generally be thought of as external (i.e., cross-connection, intrusion, main breaks, etc.) or internal (i.e., biofilms, corrosion and leaching) pathways. These designations were used in the summary tables developed in Section 7.

5.1 Pathways that Breach Distribution System Integrity

Integrity of the distribution system refers to: (1) physical integrity- the maintenance of a physical barrier between the distribution system interior and the external environment; (2) hydraulic integrity - the maintenance of a desirable water flow, water pressure, and water age, taking both potable drinking water and fire flow provision into account; or (3) water quality integrity, which refers to the maintenance of finished water quality via prevention of internally derived contamination (NRC, 2006). Breaches of distribution system physical, hydraulic, or water quality integrity may occur through the pathways listed above.

It is desirable to place boundaries on the degree/severity of breach or water quality change that should be considered, since it is impractical and unnecessary to attempt to indicate *every* type of change. Therefore, in the following discussion, each pathway is considered based on a change or breach that at a minimum would require improvements in operations and maintenance procedures. Minor water quality changes, such as minor fluctuations in temperature, pH, alkalinity, or disinfectant residual, that are inherent in daily and seasonal fluctuations associated with a well-operated treatment plant and distribution system are not considered.

5.1.1 Main Breaks, Repairs, and Installation

Contamination of pipe interiors is not uncommon during installation. Pierson et al. (2002) surveyed inspectors, engineers, and other distribution workers at three utilities about potential sources of contamination during the construction or replacement of water mains. Commonly reported sources of contamination of drinking water and pipe interior construction identified in Pierson et al. (2002) include the following:

- Broken service lines fill trench during installation;
- Pipe gets dirty during storage before installation;
- Trench dirt gets in pipe during installation; and
- Rainwater fills trench during installation.

Besner et al. (2002) summarized contamination concerns during new main installation and repair or replacement. Inadequate flushing velocities to purge contaminants from the new pipe, unsanitary conditions during work efforts, and introduction of contaminated sediment into the pipe that was not subsequently removed all create feasible contamination scenarios. The potential problem of contamination during pipe repair or installation is described more fully (including examples) in the paper titled "New or Repaired Water Mains" (AWWA and EES, 2002).

Water lines (mains and service lines) can be susceptible to contamination if they experience a break or opening and are in close proximity to sewer lines. This condition could result in contamination of the water main if the sewer line leaks and the water main experiences low or negative pressures, such as in the case of an intrusion event.

Pressure reduction or loss can occur in association with main and service line breaks. The pressure reduction or loss can result in contaminant entry (through intrusion or backflow). A 2000 American Backflow Prevention Association (ABPA) survey indicated that 19 percent and 16 percent of pressure loss events within the distribution system were attributed to main breaks and service line breaks, respectively.

5.1.2 Operation and Maintenance Deficiencies

Flushing and pigging are routine maintenance practices often conducted within the distribution system to address consumer complaints and to reduce the retention time of water to improve water quality. Utilities have typically manually flushed water from the system using fire hydrants or flushing hydrants to control microbial growth (Brandt et al., 2004). These practices can affect the distribution system water quality in a negative manner if not conducted properly. Improper flushing can result in moving a contaminant further into the distribution system.

Stagnant water can occur in dead-end pipes or storage facilities that are oversized or have periods of limited use. Stagnant water provides an opportunity for suspended particulates to settle into pipe sediments, for biofilm to develop, and for biologically mediated corrosion to accelerate (Brandt et al., 2004). Long-term water storage in finished water reservoirs (lasting weeks or several months) can result in waterborne heterotrophic bacteria growing in sediments, attaching to inner walls, and spreading a biofilm over surfaces (Geldreich, 1996). Long retention time can also result in reduction in disinfectant residual and cause the release of ammonia through the decay of chloramines (Brandt et al., 2004).

Loose deposits are susceptible to entrainment and suspension under normal hydraulic scenarios, such as flow reversals and velocity changes (Friedman et al., 2004a). Sudden flow increases (USEPA, 1992) or hydraulic disturbances (USEPA and CA DHS, 1989) can cause accumulated biofilm, scales, sediment, or tubercles to shear or slough, resulting in release to the water column. Also, if the distribution system is fed by multiple sources with varying water quality, the release of biofilms, scales, or sediments may occur at the interface between the sources.

The magnitude of pressure transients initiated by valve operations can be reduced by slowing the rate of opening and closing. When a valve is closed slowly, the rate of change of velocity in the pipeline decreases (Friedman et al., 2004b). The magnitude of transient in water mains can be as high as 100-ft (43 psi) change in head for every 1-fps change in velocity (Walski and Lutes, 1994).

5.1.3 Permeation

Permeation of piping materials and nonmetallic joints can be defined as the passage of contaminants external to the pipe through porous, nonmetallic materials, into the drinking water (Friedman et al., 2002). The problem of permeation is generally limited to plastic, nonmetallic pipe. In addition, new PVC pipes exhibit lower permeation rates than new polyethylene or polybutylene pipes (DWI0772, 1997). More than 100 incidents of drinking water contamination resulting from permeation of subsurface mains and fittings have been reported in the United States (Glaza and Park, 1992). BTEX and organic solvents are most common contaminants that permeate plastic pipe (Friedman et al., 2002).

5.1.4 Finished Covered Storage Tank Deficiencies

Storage tank deficiencies, such as vents without screens, inadequate hatches, access hatches that are not locked, and physical openings in storage tank roofs, can result in the entry of contaminants. Coatings on the storage tank interior can also result in contamination if the coating fails or is not properly cured. Potential public health issues associated with finished water storage facilities are described in a distribution system white paper on covered storage (AWWA & EES, 2002c).

5.1.5 Cross-connections and Backflow

A cross-connection is an unprotected connection between a public potable water system and any other system or source where unintended substances can be potentially introduced to the potable water supply, such as used water, industrial fluid, or gas (USC-

FCCCHR, 1993).

Backflow is the “undesirable reversal of flow of water or mixtures of water and other liquids, gases or other substances into the distribution pipes of the potable supply of water from any source or sources (USC-FCCCHR, 1993).” In order for a backflow event to occur, a cross connection and pressure loss that creates a pressure differential must exist within the distribution system, or the cross connection has created a pressure gradient in excess of normal distribution system pressure.

From 1971 through 1998, “chemical and microbial contamination from cross-connections and backsiphonage were responsible for most distribution system related illnesses. Outbreaks could be traced to backflow prevention devices that were needed but not installed, had been inappropriately installed, or had been inadequately maintained” (Craun and Calderon, 2001).

5.1.6 Intrusion

Intrusion can occur when a transient or low pressure event occurs within the distribution system that results in a lower pressure within the pipe than the pressure outside the pipe. This pressure gradient can result in contaminants contained in soil and water surrounding the distribution pipe to be “sucked” into the distribution pipe if external water pressure exceeds internal pressure (LeChevallier et al., 2002). Friedman et al. (2004b) demonstrated that transient pressure waves can travel several miles throughout the distribution system until they are dissipated, thereby increasing the potential for contamination through leakage points over a wide-spread area.

5.1.7 Biofilms

Biofilms are defined as a complex mixture of microbes, organic, and inorganic material accumulated amidst a microbially produced organic polymer matrix attached to the inner surface of the distribution system (USEPA, 2002). Contaminants, including total coliforms and some pathogens, may attach to or become enmeshed in biofilms on pipe walls in distribution systems. Many pathogens have been found to survive, if not grow, in these pipe biofilms where they are protected from disinfectants. Over time, coliform bacteria may detach or slough from the biofilm, causing persistent total coliform detections. Pathogens may also be included in the detached material and may result in waterborne disease. The biofilm can result in total coliform positive detections and other contamination events if disturbed.

Organisms that have been found in biofilms include bacteria, viruses, protozoa, invertebrates, algae, and fungi (USEPA, 2002). Less efficient treatment of source water during runoff or changing water quality conditions may cause a change in the organic matter of treated water, which in turn may enable increased biofilm growth in the distribution system (Besner et al., 2002).

5.1.8 Corrosion and Leaching

Corrosion is the gradual deterioration of metal pipe, metal fixtures, cement mortar lining in pipe, or other substances because of a reaction with the water (AWWA, 1999a).

Corrosion can be the result of physical actions that erode the coating of a pipe, chemical dissolution that leaches a pipe's lining or wall material, or electrochemical reactions that remove metal from the wall of the pipe (AWWA, 2000). Corrosion can result in the leaching of certain metals, such as lead and copper (AWWA, 2000). Biological growths within the distribution system can also cause corrosion by providing an environment in which physical and chemical interaction can occur. Leaching is defined as the dissolution of metals, solids, and chemicals into drinking water (Symons et al., 2000). Some of the factors that influence corrosion and leaching are water velocity, pipe material, and water quality within the distribution system, such as pH, alkalinity, temperature, chlorine residual, and hardness of the water.

Contaminants from pipe linings, tank coatings, fittings, or other materials can sometimes leach into the drinking water, causing contamination. Cement-lined pipes and storage tanks can leach calcium carbonate into the water, which may significantly increase the alkalinity and pH of the water. This is especially true when the cement-lined material is new, but also depends on the type of cement used, the contact time between the water and cement material, and the diameter of the pipe.

5.2 Distribution System Contamination

Contamination problems in the distribution system can occur through the pathways or breaches in distribution system integrity as described in the previous section. However, an indication of a pathway does not necessarily indicate the presence of a specific contaminant, nor does it indicate that contamination has occurred through that pathway. Hence another way of identifying a distribution system problem is to look specifically for indicators of contaminants, i.e. contaminants that pose a public health risk.

5.2.1 Fecal Contamination

Fecal contamination of distribution system water may occur when the distribution system is compromised such that a pathway has been established for fecal contaminant entry. Contamination of this type may occur through intrusion, openings in storage tanks, a broken main, or through a cross connection between a sewage source and water line. For example, in June, 2001, an employee of the Mauriceville Special Utility District in Texas inadvertently connected a sewer line to a fresh water line (U.S. Water News Online, 2001). As a result, sewage contaminated the drinking water supply for about 20 days before customer complaints about particles in the water prompted the utility district to conduct sampling. The samples came back positive for fecal coliform bacteria and resulted in an acute TCR violation.

5.2.2 Toxic or Carcinogenic Contamination

Toxic or carcinogenic contamination can enter through external pathways that result in contamination of the distribution system, similar to fecal contaminants. The events that can lead to this type of contamination include intrusion, openings in storage tanks, broken mains, permeation, or through a cross connection between a non-potable source and water line. Examples of toxic and carcinogenic contaminants include organic compounds (e.g. PCBs, benzene), heavy metals (e.g., lead, mercury, cadmium), asbestos, and others.

Toxic and carcinogenic contaminants can also manifest within the distribution system, such as in the case of biofilms, corrosion, and leaching. In addition, modification to O&M practices or to treatment practices can cause the release of contaminants in established pipe scales due to changes in pH, alkalinity, or other water quality parameters. A separate White Paper is currently under development that addresses accumulation and release of inorganic contaminants in distribution systems.

5.3 Public Health Outcome

Public health outcomes such as waterborne disease outbreaks and endemic illness may occur, but do not always occur, following a contamination event. Likewise, indicators of pathways or indicators of contaminants may not always indicate a public health outcome.

5.3.1 Waterborne Disease Outbreaks and Endemic Illness

Ingestion of distribution system water containing pathogens, toxins, or carcinogens can result in illness. In some instances, the illness may go unnoticed by water system personnel or public health officials, and in other instances, officials may be unable to link the illness with the water system. The latter scenario can occur when the affected population believes the illness may have been foodborne, where follow-up testing of the distribution system could not detect the presence of the contaminant, or when the number of people affected may not have triggered notice by the public health community.

However, illnesses may be recognized by local public health officials or others, and in some instances, reported to the Centers for Disease Control and Prevention (CDC). CDC’s investigation will determine if the contamination event meets the two criteria for a waterborne disease outbreak. First, a waterborne disease outbreak is defined as when two or more individuals have experienced a similar illness after ingestion of water or exposure to water. If water quality data indicate chemical contamination or laboratory-confirmed primary amebic meningoencephalitis, a waterborne disease outbreak is defined as when one or more individuals experience illness. Second, epidemiological evidence must implicate ingested water as the probable source of illness (CDC, 2004).

There is evidence of significant under-reporting of the number of outbreaks and illnesses associated with these outbreaks due to inherent limitations in detecting them and biases in reporting them. For example, most local surveillance systems are passive—i.e., the disease reporting is primarily the responsibility of the health care provider and/or laboratory (Frost et al., 1996). Frost et al. (1996) noted that "health care providers and laboratories usually receive little encouragement from the health department to report illnesses, and enforcement of reporting requirements is minimal." In addition, only a fraction of illness-causing agents are reportable to the CDC. CDC has identified 52 nationally notifiable diseases that might be waterborne, including cryptosporidiosis, giardiasis, salmonellosis, typhoid fever, legionellosis and shigellosis. States, however, are not obligated to include these diseases in their own surveillance programs. A 1997 survey revealed that approximately 87 percent of state health departments include 80 percent of the 52 nationally notifiable diseases in their surveillance programs. Only about one-third of states include over 90 percent of the diseases (GAO 1999). Some of the pathogens associated with distribution system contamination are not on CDC's list. Moreover, CDC does not have a comparable list for toxic chemicals.

6 Indicators

The discussion for each indicator provides background information, identifies potential distribution system problems that the indicator may demonstrate or predict vulnerability to, and discusses advantages and disadvantages of the indicator.

Under every indicator, each category of distribution system problems is considered: Indicators of pathways that breach distributions system integrity; Indicators of distribution system contamination; Indicators of Public Health Outcome. However, if information was not readily available for a category, that category was omitted from the discussion.

6.1 Microbial Indicators

6.1.1 Total Coliforms

Background

Total coliforms are defined as gram negative, non sporeforming, facultatively anaerobic rod-shaped bacteria capable of lactose-fermentation with gas production at 35°C within 48 hours. The group consists of several genera of the family Enterobacteriaceae, including species *Enterobacter*, *Klebsiella*, *Citrobacter*, and *E. coli*. Total coliforms may be of fecal origin, but also survive and grow in the environment (Flint, 1987; Pommepuy et al., 1992). Total coliforms have been used as an indicator of drinking water quality since the early 1900s. The rationale for using total coliforms in this manner is based on their presence in large numbers in the gut of humans and other warm blooded animals, allowing their detection even after extensive dilution (Stevens et al., 2001). Although not typically pathogens themselves, they are used to indicate the potential for pathogenic organisms to be present (52 FR 42226; Nwachuku et al. 2002). However, where other problems are not evident (e.g., cross-connections or treatment deficiencies), a persistent coliform problem may indicate biofilm growth problems (Edberg, 1994; O'Neill and Parry, 1997; Crozes and Cushing, 2000). Investigators have identified several species of coliforms that can grow in pipe biofilms, including

Enterobacter cloacae, *Klebsiella oxytoca*, *Citrobacter freundii*, and *Enterobacter agglomerans* (Geldreich, 1996).

Total coliforms are typically associated with treatment effectiveness, and should be absent from adequately treated plant effluents (LeChevallier et al., 1991, 1996, 1999; Craun et al. 1997, 2001). The presence of total coliforms in the distribution system while possibly due to inadequate treatment, could also be due to cross-connections or failure to maintain an adequate disinfectant residual (LeChevallier, 1996). Coliforms present in the distributions system can come from a number of sources, and they can also grow within the distribution system, in biofilms as discussed below. Simple, inexpensive analytical methods are available (Rompre et al., 2002).

Total coliforms are usually effectively inactivated by disinfectant residuals commonly encountered in distribution systems. They show less resistance to disinfectants than *Giardia*, *Cryptosporidium*, and some viruses.

Indicator of Breaches Distribution System Integrity

While coliforms may be used as an indicator of treatment effectiveness, they can be introduced or grow within the distribution system. As discussed above total coliforms can indicate distribution system integrity problems such as cross-connections, intrusion, or presence of biofilms. In some cases, it may be difficult to identify a specific pathway or breach of distribution system integrity using total coliforms as an indicator.

Total coliforms have been identified as a component of biofilms (Edberg, 1994; O'Neill and Parry, 1997; Crozes and Cushing, 2000). Environmental conditions in the distribution system where the water temperature is above 15ºC, the pH is neutral, and AOC concentrations are adequate, favor the colonization of total coliform bacteria on surfaces within the distribution that may become part of a biofilm (WHO, 2004). Investigators have identified several species of coliforms that can grow in pipe biofilms, including *Enterobacter cloacae*, *Klebsiella spp*., *Citrobacter freundii*, and *Enterobacter agglomerans* (Geldreich, 1996). LeChevallier et al. (1987) studied distribution system biofilms at a water utility in New Jersey and found that coliforms moved from the treatment plant into the distribution system, and were found in increased numbers at sites corresponding to growth of biofilm. While total coliforms may be an indicator of the presence of biofilms, they are not uniformly associated with biofilms (LeChevallier, 1987; Characklis, 1986), nor do they only occur because of the presence of biofilms as suggested by the multiple potential pathways outlined above.

Indicator of Distribution System Contamination

Some of the total coliform bacteria are capable of growth in environmental conditions, which may limit their use as indicators of fecal contamination in a water system. A subset of the total coliform group is the fecal coliform group, which is believed to serve as better indicators of fecal contamination. *E. coli* and fecal coliforms are thought to be good fecal indicators and are part of the total coliform group.

Indicator of Public Health Outcome

Total coliforms may be adequate for predicting a system's vulnerability to bacterial pathogens, but may not be sufficient for predicting a system's vulnerability to an outbreak from other microbial contaminants, such as protozoa and viruses (Nwachuku et al., 2002).

Craun et al. (1997) reviewed epidemiologic investigative reports of waterborne disease outbreaks and available data from 1983-1992 (Exhibit 2). The authors examined the percent of outbreaks where total coliforms are present, depending on the system type and the type of outbreak. This research finds different rates depending on the type of system and outbreak. The authors also noted that increased sampling for coliform organisms, above that required for compliance monitoring, may have occurred during the outbreaks. In addition, the authors cautioned that the data were limited and could not rule-out the influence of random error.

Exhibit 2: **Summary of Findings from Craun et al. (1997)**

	Systems with Total Coliforms Present During Outbreak Investigations (of 157 outbreaks with available information)	**Systems with Total Coliforms Present During Outbreak Investigations Where**:			
		Outbreaks Attributed to Treatment Inadequacy	Outbreaks Attributed to Distribution or Unknown Deficiency	Outbreaks Caused by Bacteria, Viruses, or Unidentified Agents	Outbreaks Caused by *Giardia* or *Cryptosporidium*
Community	52%	48%	63%	64%	35%
Non-community	87%			90%	
Individual (nonpublic)	93%			93%	
All Systems	73%				

Note: Shaded boxes indicate data not provided

In a comparison of TCR violations for water systems that had or had not reported an outbreak during 1991-1998, Nwachuku et al. (2002) concluded that when all etiologies were considered for community water system outbreaks, the outbreak systems were more likely than non-outbreak comparison systems (p<0.05) to have reported an MCL violation in the 3-and 12-month periods before the outbreak. Although the focus of the paper was on the TCR, the authors also concluded that their analyses, along with disinfection information, showed that coliform bacteria and the TCR are insufficient to assess an increased risk of waterborne disease outbreaks from *Giardia* and *Cryptosporidium* and may be insufficient for some viruses (Nwachuku et al., 2002

The research concluded that current, routine monitoring under the TCR was not adequate to predict waterborne outbreak vulnerability, and that additional monitoring in combination with an additional indicator may be more reliable.

Advantages

Total coliform densities are much greater than the density of fecal indicators (Payment et al., 1985). Total coliform bacteria are useful in assessing treatment effectiveness and breaches in the distribution system as well as a water system's vulnerability to fecal contamination, as stated above (Craun and Calderon, 2001). Detection methods for total coliform bacteria are simple and inexpensive, and laboratories are familiar with these methods (Rompre et al., 2002).

Disadvantages

It cannot easily be determined if total coliforms are of fecal or environmental origin. They are not ideal indicators because they are more sensitive to disinfection than some pathogens.

Total coliforms are not good indicators of specific contamination pathways. They are not uniformly associated with biofilms nor is their presence exclusive to biofilms. Total coliforms can also be present due to a number of pathways such as treatment breakthrough, cross-connections and intrusion.

Total coliforms do not appear to be good indicators of vulnerability to waterborne outbreaks, without investing in additional monitoring beyond current TCR requirements, and possibly in conjunction with another indicator.

High levels of heterotrophic bacteria can interfere with total coliform analysis in lactose-based culture methods, whereby method interference can occur when the HPC densities exceeded 500 cfu/mL (Geldreich et al., 1972). Experimental studies have also shown that high levels of HPC bacteria can out-compete coliform organisms for low levels of nutrients (LeChevallier and McFeters, 1985).

6.1.2 Thermotolerant (Fecal) Coliforms

Background

Thermotolerant coliforms are now the preferred designation for the group of bacteria previously referred to as fecal coliforms (WHO, 1996). This group of organisms, which are distinguished from other members of the total coliform group by their ability to ferment lactose at a specified elevated temperature, includes thermotolerant strains of the genera *Klebsiella*, *Escherichia*, *Enterobacter* and *Citrobacter* (WHO, 2004). In drinking water, *E. coli* typically comprises the majority of the thermotolerant coliforms isolated. For example, Warren et al. (1978) determined that 96.96% of a single thermotolerant coliform sample was *E. coli*, 2.32% was *E. cloacae*, 0.66% was *K. pneumoniae*, and 0.33% was *C. freundii*.

The presence of thermotolerant coliform bacteria is thought to correlate with the presence of enteric pathogens in the environment (Bulson et al., 1984). In general, thermotolerant coliform bacteria are relatively reliable as indicators for disease-causing bacteria, and slightly less effective in determining the presence of viral and protozoan pathogens compared to bacteria (Reynolds et al., 2003).

Because environmental strains of certain organisms are included in the thermotolerant coliform group and growth within distribution systems has been reported in biofilms (Fass et al., 1997), their presence cannot explicitly be related to fecal matter.

Indicator of Breaches of Distribution System Integrity

Thermotolerant coliforms in the distribution system may originate from sources outside the distribution system, which could indicate that a pathway exists for fecal contamination of distribution system water due to cross-connection or distribution system intrusion. However thermotolerant *Klebsiella* and other coliforms are capable of growth in biofilms and may serve as an indicator of biofilm growth (Fass et al., 1996). The multiple pathways and sources for thermotolerant coliforms suggest difficulty using these organisms alone to indicate a particular pathway or source of contamination, and hence a targeted remedial action. The density of thermotolerant coliforms is lower than the level of total coliforms since thermotolerant coliforms are a subset of the total coliform group. While thermotolerant coliforms are a more specific fecal indicator, the lower density of thermotolerant coliforms in distribution system water relative to total coliforms may mean that they are a less sensitive fecal indicator.

Indicator of Distribution System Contamination

Thermotolerant coliforms are more closely linked to fecal contamination than total coliforms. However, the presence of thermotolerant coliforms can not be explicitly related to fecal matter.

Indicator of Public Health Outcome

Thermotolerant coliform bacteria are relatively reliable indicators of disease causing bacteria (Reynolds et al., 2003).

Advantages

Analytical methods are simple, reliable, inexpensive, and produce results within 48 hours. Laboratories are familiar with the test methods (APHA, 1995). In comparison with *E. coli*, thermotolerant coliforms are typically found in greater densities and are therefore easier to detect than *E. coli* (Davis et al., 2005). With respect to total coliforms, thermotolerant coliforms are a more specific indicator of fecal contamination than total coliforms (Cabelli, 1977). Most thermotolerant samples are associated with recent fecal contamination.

Disadvantages

Some environmental strains of *Klebsiella* and other strains of total coliforms are detected using analytical methods for thermotolerant coliforms making this indicator less reliable than *E. coli* for determining the presence of fecal contamination (WHO, 2004). *Pseudomonas* spp. are antagonistic to fecal indicator organisms, and their presence in distribution water may affect performance of compliance monitoring tests for fecal coliforms and *E. coli* (Wernicke and Dott, 1987).

E. coli is normally present in a fecal coliform-positive sample; therefore, the disadvantages of using *E. coli* would apply. That is, they may die out more quickly than some waterborne pathogens due to succumbing to environmental factors or to inactivation by disinfectants, and have been reported to grow in the environment in tropical waters and soils.

In comparison with total coliforms, thermotolerant coliforms are found in water at a lower density than total coliforms and are thus harder to detect.

Thermotolerant coliforms could be present in the distribution system due to various pathways and contamination events or growth in biofilms. It may be difficult to determine the source based only on this indicator.

The presence and detection of fecal coliforms in the distribution system constitutes an acute violation of the TCR (40 CFR § 141.63 (b)).

6.1.3 Escherichia coli

Background

Escherichia coli is a member of the family *Enterobacteriaceae* and is included in the total coliform and fecal coliform group of bacteria. *E. coli* are abundant in human and animal feces and thus can be found in sewage and wastewater treatment effluent. *E. coli* have been used as indicators of fecal water contamination for over 50 years (Schubert and Mann, 1968; Weber-Schutt, 1964). The presence of *E. coli* in water is strong evidence of human or animal fecal contamination, which suggests that enteric pathogens may also be present. *E. coli* has replaced thermotolerant (fecal) coliform bacteria as the principal fecal indicator for water and wastewater (WHO, 1993), although fecal coliform monitoring is still required under the Surface Water Treatment Rule and is still allowed under the TCR. Although traditionally believed to have a relatively short survival time in the environment in temperate climates, *E. coli* is correlated with point source pollution of inadequately treated wastewater, septic tanks, and livestock discharge. Recently, *E. coli* has been reported to grow in soils and water in tropical climates (Solo-Gabriel et al., 2000).

Indicator Breaches of Distribution System Integrity

E. coli may be used to indicate that distribution system water is vulnerable to fecal contamination due to a variety of pathways, including distribution system intrusion, contaminated storage, or cross-connections. However evidence suggests that *E. coli* may potentially also survive and grow in distribution system biofilms. Further information about whether a sudden occurrence of *E. coli* may be more likely due to a contamination event versus from biofilm growth could be useful in characterizing *E. coli* as an indicator.

Fass et al. (1996) injected two nonpathogenic strains of *E. coli* into a pilot distribution system with a biofilm at 20° C and noted the *E. coli* grew slightly before eventually dying out.

Several studies have shown that *E. coli* can survive in biofilms in distribution systems (Olson, 1982; LeChevallier, 1987). Another study by Camper et al. (2003) found that environmental isolates of *E. coli* removed from a New Haven, Connecticut drinking water system as well as an enterotoxigenic *E. coli.* strain experienced growth under conditions representative of municipal drinking water systems. In model distribution system biofilms, exposed to either hypochlorous acid or monochloramine, *E. coli* cells were able to survive at least 10 days in distribution system biofilms, even under high levels of disinfection (Williams et al., 2003).

Indicator of Distribution System Contamination

The presence of *E. coli* in distribution system water is strong evidence of human or animal fecal contamination, which suggests that enteric pathogens may also be present. *E. coli* have the same resistance to environmental factors as other enteric bacteria. However, *E. coli* are more sensitive to environmental factors than viruses and cysts or oocysts of pathogenic protozoa. While *E. coli* is a more specific fecal indicator than total coliforms or thermotolerant coliforms, the low density of *E. coli* in distribution system water relative to total and thermotolerant coliforms may mean that it is a less sensitive fecal indicator.

Indicator of Public Health Outcome

Several studies have found that the concentration of *E. coli* in drinking water significantly correlates with the presence of gastrointestinal illnesses. For example, Moe et al. (1991) examined the effectiveness of indicator bacteria in predicting gastrointestinal disease in individuals less than 2 years old in the Philippines. *E. coli* and enterococci were found to be more reliable predictors of the risk of gastrointestinal disease compared to thermotolerant coliforms or fecal streptococci. Raina et al. (1999) also found a significant association between *E. coli* in well-water of rural Canada, and gastrointestinal illness in family members. Similarly, Strauss et al. (2001) determined that the odds ratio to contract a GI illness for individuals exposed to *E. coli* was 1.52 compared to those who were exposed to *E. coli* levels below current U.S. and Canadian standards. Total coliforms had an odds ratio of only 0.39. Further, Noble et al. (2004) determined that *E. coli* survives longer than enterococci in sunlight exposed sewage and run-off. In addition, Strauss et al. (2001) hypothesized that *E. coli* is a more reliable predictor than thermotolerant coliforms since *E. coli* is a more specific measure for fecal contamination than the general category of thermotolerant coliforms, which is comprised of multiple species.

To determine the potential for using *E. coli* as an indicator of water quality, many studies examined the association between *E. coli* in recreational waters and the prevalence of GI illnesses. For example, Wade et al. (2003) conducted a systematic review of over 25 peer-reviewed and governmental studies that examined the relationship between *E. coli*, enterococci and other bacterial indicators with GI illness. Their research demonstrated that in freshwater, *E. coli* was the most consistent predicator of GI illness, whereby a log unit increase in *E. coli* was associated with a 2.12 increase in relative risk for contracting a GI illness. Likewise, an earlier review of peer-reviewed literature indicated that *E. coli* best correlates with health outcomes in freshwater (Pruss, 1998). These results parallel EPA's recommendations in 1986, which suggest that *E. coli* should be used as an indicator of water quality in fresh recreational waters (USEPA, 1986).

Advantages

Analytical methods are simple, reliable, inexpensive and produce results within 24 to 48 hours (Brenner et al., 1993). *E. coli* is closely associated with recent fecal contamination and is found in high concentrations in sewage and septage. (Cabelli, 1977; WHO, 1994) *E. coli* is extremely sensitive to disinfection and its presence would indicate a major deficiency in the distribution system (Noble et al., 2004; WHO, 2004).

Disadvantages

The density in water of *E. coli* is less than that of total coliforms. *E. coli* may be more sensitive to environmental factors or to inactivation by disinfectants than some waterborne pathogens. Since *E. coli* can be inactivated through disinfection, fecal contamination that enters the distribution system may not be detected if *E. coli* is the only indicator used (WHO, 2004). However in the event of a sewage contamination, the loss in disinfectant residual (LeChevallier, 1999) could be an alternative indicator. *Pseudomonas* spp. and other HPC bacteria may interfere with the methods used for fecal coliforms and *E. coli* (Wernicke and Dott, 1987).

6.1.4 Heterotrophic Bacteria as Measured by the HPC Method

Background

Heterotrophic bacteria are a broad class of organisms that use organic nutrients for growth. The group includes harmless environmental bacteria, virtually all pathogenic bacteria, and opportunistic pathogens (bacteria that cause a disease in a comprised host but that are unlikely to cause a disease in an uncompromised host). Opportunistic pathogens include strains of *Pseudomonas aeruginosa*, *Acinetobacter* spp., *Aeromonas* spp., *Klebsiella pneumoniae*, and others. However, these opportunistic pathogens are not detected with the media used for HPC determination (WHO, 2002).

The number of heterotrophic bacteria recovered from a water sample will depend on the procedures and isolation medium used, and on the interaction among the developing colonies (APHA, 1995). The population of these bacteria is often measured by the Heterotrophic Plate Count (HPC) procedure (Standard Method 9215), previously referred to as the standard plate count procedure. Other methods of measuring heterotrophic bacteria would include total bacteriological count, total viable bacterial count, adenosine triphosphate, and endotoxin. These methods and their use as indicators in drinking water are discussed in other sections of this document.

The range of heterotrophic bacteria usually measured in drinking water is <0.2 CFU/ml to 10,000 CFU/ml or higher (Allen et al., 2002). No validated epidemiological evidence links consumption of high levels of heterotrophic bacteria in drinking water to increased health risks (Leclerc, 2002).

Measurements of heterotrophic bacteria may be useful in managing distribution system water quality for the following (Reasoner, 1990):

- Monitoring the efficiency of the treatment process
- Evaluating changes in finished water quality and distribution system cleanliness
- Assessing bacterial growth in the distribution system
- Measuring bacterial growth contributed by treated drinking water
- Comparing bacterial populations in the distribution system before and after treatment process changes (e.g., type of disinfectant, disinfectant concentrations or level of filtration).

Indicator of Breaches of Distribution System Integrity

HPC measurements provide an indication of general water quality within the distribution system (WHO, 2003a). An increase in HPC can be an indication of treatment breakthrough, contamination introduced post-treatment during main breaks, repairs, and installation or through intrusion, microbial growth within the distribution system, or the presence of deposits and biofilms (WHO, 2004). An increase in HPC bacteria may also be due to nitrifying distribution conditions for chloraminated systems (AWWA and EES, 2002d).

HPC measurements can be used to assess microbial growth on materials used in water distribution systems and for determining the extent of growth in distribution water. Growth of heterotrophic bacteria associated microorganisms can occur as biofilms, and is typically reflected in water samples as higher HPC values (WHO, 2002). LeChevallier et al. (1987) studied distribution system biofilms at a water utility in New Jersey and found that HPC moved from the treatment plant into the distribution system, and were found in increased numbers at sites corresponding to growth of biofilm. Biotyping of coliforms and heterotrophic plate counts were used to detect and monitor locations with biofilm growth. Where biofilm can be ruled out as the cause, elevated counts of heterotrophic microorganisms can be used to indicate distribution system integrity problems of a nonfecal nature.

Heterotrophic bacteria levels respond to conditions in the distribution system that include stagnation, loss of residual disinfectant, high levels of AOC in the water, higher water temperature, and availability of particular nutrients. They are also useful for determining changes in water quality in the distribution system. Carter et al. (2000) found correlations between HPC counts using R2A agar and pH, conductivity, temperature, and disinfectant residual in the distribution system.

While total coliform tests are useful in identifying a problem and perhaps in localizing a problem within the distribution system, the use of HPC and other methods is necessary to characterize contamination and biofilm occurrences (Edberg, 1994).

Indicator of Distribution System Contamination

With respect to being an indicator of fecal contamination, WHO (2003a) concluded that in situations where fecal contamination is not present, HPC levels do not correlate to health effects to the general population. EPA (1996) concluded that because increased levels of HPC do not correlate to an increased likelihood of fecal contamination, heterotrophic bacteria are not reliable indicators.

Indicator of Public Health Outcome

Current research suggests that heterotrophic bacteria are not appropriate indicators for waterborne disease outbreaks or endemic illness risks (WHO 2002, 2003a, Allen et al., 2004). The World Health Organization expert meeting on the role of heterotrophic measurements in drinking water quality and safety concluded that there is no evidence of an association with gastro-intestinal infection through the waterborne route among the general population and heterotrophic bacteria (WHO, 2003a). Allen et al. (2004) examined 11 health studies and determined that there was no evidence to support health-based regulations of HPC concentrations. Pavlov et al. (2004) concluded that heterotrophic bacteria health risks were confined to a small percentage of the population, such as the very young, very old, AIDS patients, and patients on therapy for organ transplantation or cancer treatment.

Advantages

Heterotrophic microorganisms are a general indicator of microbial water quality conditions. They are also effective indicators of bacterial growth (WHO, 2002). The Standard HPC method is simple, inexpensive, and produces results within 48 hours (Exner et al., 2003).

Disadvantages

In the report entitled "*Heterotrophic Plate Count Measurement in Drinking Water Safety Management*," the WHO concluded there is no evidence that heterotrophic bacteria counts alone directly relate to health risk either from epidemiological studies or from correlation and occurrence of waterborne pathogens (WHO, 2002).

High measurements of heterotrophic bacteria can be indicative of a range of issues, and cannot be used to determine if the problem is of fecal origin.

HPC measurements can lead to unreliable results. For example, the population of microorganisms recovered in an HPC test will differ significantly depending upon the type of test used, the location of the sample, the season the sample was taken, and the number of consecutive samples taken at a single area (WHO, 2002).

Standard HPC methods are insensitive to waterborne bacteria.

6.1.5 Total Bacteriological Counts and Total Viable Bacterial Counts

Background

Total bacterial counts reveal the number and variety of bacterial populations present in a sample. This measurement enables enumeration of those populations that will not grow on artificial media, and comprises the full number of viable, viable but non-culturable, and nonviable organisms present in a water sample. Total bacterial counts are conducted microscopically using fluorescent dyes such as acridine orange, which stains nucleic acids (APHA, 1995). More complex techniques can be used to discern serotype and genetic content information (WHO OECD, 2003b). Total bacterial counts are less specific than total coliforms and would produce a higher hit rate than total coliform sampling.

A viable cell is one that can divide and form offspring (Madigan, 2006). Measurement of total viable bacterial counts is based on the ability of the organisms to grow using specific culture methods, although staining techniques are sometimes used. Viable counts have been used as a measure of water quality since bacteriological methods permitting enumeration of microorganisms were first introduced in the late 1800s. These methods have been referred to by a variety of names, including total bacterial count, total plate count, colony count, standard plate count, total viable count, and heterotrophic plate count (HPC). Slight variations in the methods and medium will affect the organisms recovered from the water sample; some procedures use low nutrient agar to target recovery of stressed organisms while others may contain ingredients that support growth of bacteria that have virulence factors related to their ability to cause waterborne disease.

Total bacterial counts are less specific than HPC in terms of medium and incubation conditions. Total viable counts will have similar applications, advantages, and disadvantages as do results obtained using the HPC method.

Indicator of Breaches of Distribution System Integrity

Elevated bacterial counts can potentially be used to indicate distribution system integrity problems of a nonspecific nature including intrusion, loss of disinfectant residual, stagnation, and an increase in nutrient levels in the water.

Total viable counts are useful for determining changes in water quality during water storage and distribution (Carter et al., 2000), and can be used to assess microbial growth on materials used in water distribution systems and for determining the extent of growth in distribution water. Viable heterotrophic bacteria levels respond to stagnation, loss of residual disinfectant, high levels of AOC in the water, higher water temperature, and availability of nutrients (Reasoner, 1990).

As with heterotrophic bacteria, total viable counts and total bacterial counts can be used to detect and monitor biofilm growth in the distribution system.

Advantages

Total bacterial counts, whether based on culture methods or direct counts, provide basic information on the numbers of bacteria in water. OECD WHO (2003b) notes that although actual bacterial counts are of limited value, significant changes in viable counts normally found at particular locations may warn of significant problems.

The methods for viable counts that rely on culture methods are relatively simple to perform, are inexpensive, and are familiar to laboratory personnel (Gunasekera et al., 2000). Total bacterial counts capture bacteria that will not grow on artificial media.

Disadvantages

Total bacterial counts, whether viable or nonviable, are nonspecific and do not provide an index of fecal contamination or waterborne disease outbreaks. As noted in the HPC discussion, the WHO report, *"Heterotrophic Plate Count Measurement in Drinking Water Safety Management*," concluded there is no evidence that heterotrophic bacteria counts alone directly relate to health risk either from epidemiological studies or from correlation and occurrence of waterborne pathogens (WHO, 2002). Total counts cannot distinguish viable and nonviable cells and is a microscopic method which is tedious and time-consuming (Gunasekera et al., 2000).

6.1.6 Pseudomonas and Aeromonas

Background

Pseudomonas and *Aeromonas* spp. are Gram-negative, rod-shaped, oxidase positive, non-spore forming bacteria that occur naturally in the environment. *P. aeruginosa* is commonly found in feces, soil, water, and sewage (OECD WHO, 2003b). *Aeromonas* is not associated with fecal pollution, but is capable of growth in distribution mains and storage tanks. Pseudomonads and *Aeromonas* spp. have been isolated from biofilms (van der Kooij and Hijnen, 1988) and are able to grow in low nutrient conditions (Ribas et al., 2000).

The Dutch standard for *Aeromonas* levels is 20 cfu/100 mL in finished water and 200 cfu/100 mL in distribution water (van der Kooij, 1988).

Indicator of Breaches of Distribution System Integrity

Aeromonas and *Pseudomonas* have been proposed as indicators of distribution system integrity because they are common environmental organisms (WHO, 1996). Further, the presence of *Aeromonas* spp. in water distribution systems suggests inadequate chlorine residuals or the potential for biofilms (Stelzer et al., 1992). The growth of these microorganisms in the water distribution system is often most favorable when there is a low concentration of biodegradable dissolved organic carbon (BDOC). *Pseudomonas* has been proposed as an indicator of bacterial growth since it has a greater affinity with some of the components of the BDOC than other bacteria (van der Kooij et al. 1982).

Pseudomonas and *Aeromonas* have been recovered from biofilms. In Barcelona, Spain, both *Pseudomonas* and *Aeromonas* were considered useful potential indicators of bacterial growth, although *Pseudomonas* was deemed a better indicator (Ribas et al., 2000). Stelzer et al. (1992) came to a similar conclusion after analyzing the drinking water supply in Germany.

Indicator of Distribution System Contamination

P. aeruginosa is not an indicator of fecal contamination since it is not always present in feces and sewage and may multiply in the environment (OECD WHO, 2003b). There have been mixed findings as to whether *Aeromonas* indicates fecal contamination. In Cameroon, Nola et al. (1998) found that *Aeromonas hydrophila* in well water was strongly correlated with the density of fecal bacteria. However, in Italy, Legnani et al. (1988) did not find a correlation between the concentration of *Aeromonas* spp. and fecal indicator organisms. *Aeromonas* is easily reduced though treatment, but high levels can still be found in the distribution system as a result of regrowth (OECD WHO, 2003b).

While not an indicator of fecal contamination, the presence of *P. aeruginosa* may be one of the factors taken into account in assessing bacterial contamination in general as its presence may signify a deterioration in bacteriological quality (OECD WHO, 2003b).

Indicator of Public Health Outcome

In Mexico, De Victorica and Galvan (2001) documented an outbreak of *E. coli* and *P. aeruginosa*, where there was a primary infection by *E. coli* and a secondary infection by *P. aeruginosa* in 5 children. De Victoria and Galvan (2001) concluded that *P. aeruginosa* should be used as an indicator of waterborne diseases.

Although no major outbreak has been documented with direct links to public water supplies, increased *Aeromonas* occurrences were reported from the Netherlands and Australian water supplies in which warmer months were correlated with increased *Aeromonas* associated gastroenteritis (Burke et al., 1984; van der Kooij, 1988b) (Havelaar et al., 1990). Other workers from Cairo, Egypt, have claimed that the domestic water supply was responsible for increased gastroenteritis cases, based on the fact that 90 % of their water supplies tested positive for *Aeromonas* (Ghanem et al., 1993).

Some *Aeromonas* species are considered opportunistic pathogens and may cause GI illness. For example, *Aeromonas hydrophila* can produce cytotoxins and enterotoxins associated with acute gastroenteritis (Fernandez et al., 2000). In Auckland, New Zealand, Simmons et al. (2001) determined that households that reported at least one case of gastrointestinal symptoms in the month prior to sampling were significantly more likely to have water samples containing *Aeromonas* spp., with an odds ratio of 3.22.

Advantages

Pseudomonas and *Aeromonas* may be useful in indicating an inadequate chlorine residual or the presence of biofilm growth. They are both detectable by simple, inexpensive methods that can be applied in a basic bacteriological laboratory (OECD WHO, 2003b).

Disadvantages

Pseudomonas and *Aeromonas* capture a smaller variety of biofilm bacteria compared to other potential indicators. Also, because of the motility and growth of *Pseudomonas* on certain growth media, they may interfere with the recovery of other organisms.

6.1.7 Enterococci and Fecal Streptococci

Background

Hardie and Whiley (1997) published a classification and overview of the genera *Streptococcus* and *Enterococcus*. They describe the organisms as Gram-positive, non-spore forming, spherical or ovoid cells which are typically arranged in pairs or chains and are widely distributed, mainly on mucosal surfaces of humans and animals. Some are also found in soil, dairy products and other foods, and on plants. Enterococci are typically found in the intestinal tract and feces of humans and other animals, they generally do not grow in the environment except in tropical climates, and they have been shown to survive longer than *E. coli* (Hardina and Fujioka, 1991; McFeters et al., 1974). For these reasons, WHO generally regards them as specific indices of fecal pollution from warm blooded animals (OECD WHO, 2003b). The predominant intestinal enterococci are *E. faecalis*, *E. faecium*, *E. durans*, and *E. hirae*. Some species such as *S. pyogenes* and *S. pneumoniae* are human pathogens.

Althaus et al. (1982) studied the species of fecal streptococci using differential and selective media and found that some species were characteristically isolated from a particular source. *S. faecalis* predominates in human waste, while *S. faecium* and *S. durans* were isolated specifically from sewage and wastewater. Selection of culture media and methods determines to a great extent which species are isolated. Fecal streptococci do not grow in water (Brezenski, 1973; Geldreich, 1973), and they survive longer in winter than in summer (Cohen and Shuval, 1973; Van Donsel et al., 1967). Sinton et al. (1993a; 1993b) published reviews of fecal streptococci as pollution indicators.

Indicators of Breaches of Distribution System Integrity

The presence of enterococci indicates a contamination pathway exists for fecal material to enter the distribution system. Fecal streptococci are more resistant to stress and chlorination than *E. coli* and the other coliform bacteria (OECD WHO, 2003b). They are also highly resistant to drying and thus may be valuable for routine control after new water mains are laid or distribution systems are repaired (OECD WHO, 2003b).

Indicators of Contamination

Enterococci, *E. coli*, total coliforms, fecal coliforms, *P. aeruginosa*, and *A. hydrophila* were studied as water quality indicators (Miescier and Cabelli, 1982). Among these, enterococci best satisfied the requirement for a fecal indicator. Enterococci survive secondary sewage treatment better than *E. coli*, they do not generally multiply in the environment, and they are consistently associated with fecal wastes for humans and animals. In a study by Pinto et al. (1999), the majority of enterococci (84 percent) isolated from a variety of polluted water sources were true fecal species.

Indicators of Waterborne Outbreaks or Endemic Disease

Zmirou et al. (1987) conducted an epidemiological study that examined the effectiveness of indicator monitoring at preventing human disease from treated drinking water. Heterotrophic plant count, total coliforms, thermotolerant coliforms, and fecal streptococci monitoring results were examined, together with the number of cases of acute gastrointestinal disease in 52 French villages. A log linear model identified fecal streptococci as the best predictor of human disease, and the association between monitoring results and human gastrointestinal disease was stronger when both fecal streptococci and thermotolerant coliforms were positive. Heterotrophic plate counts and total coliforms made no independent contribution to the ability to predict disease risk; however any level of indicator bacteria above zero was associated with increased rates of gastrointestinal disease.

Advantages

Standardized methods are available, are relatively easy to use, and provide rapid results (USEPA, 1996). Fecal streptococci and enterococci are present in wastewater and known polluted water; the organisms are generally absent from pure, unpolluted waters having no contact with human and animal life (the exception being growth in soil and on plants in tropical climates (Hardina and Fujioka, 1991)).

Disadvantages

As an indicator of treatment effectiveness and distribution system integrity, enterococci and fecal streptococci are present in lower numbers than total coliforms. They are also not as good a fecal indicator when pathogenic protozoa are present. Pathogenic protozoa such as *Giardia* and *Cryptosporidium* are more resistant to environmental stress and disinfection than enterococci and fecal streptococci.

6.1.8 Somatic Coliphage

Background

Bacteriophages are viruses that infect bacteria, and those that infect *E. coli* are called coliphages. Somatic coliphages are viruses that infect host cells through the outer cell membrane. The host bacterium and its density, temperature, pH, and other variables affect the incidence, survival, and behavior of phage in different water environments (Stevens et al., 2001). The impacts of these variables affect the consistency of data and comparisons of bacteriophages in water environments.

Coliphages have been proposed as virus surrogates for water disinfection and treatment studies. The theory behind the use of coliphage as an indicator of water quality is based on the premise that these viruses will behave more like human enteric viruses than do bacterial indicators. In addition, they have also been proposed as sewage indicators because of their constant presence in feces, sewage, and polluted waters.

Indicator of Breaches of Distribution System Integrity

The presence of somatic coliphage may not be a useful indicator of a distribution system integrity problem, even when the problem involves the introduction of fecal contamination. LeChevallier et al. (2006) measured the presence of somatic coliphage in the distribution system, finding that of nearly 400 samples, the only samples containing somatic coliphage were attributed to a contaminated control sample rather than a breach in the distribution system. These distribution system samples were collected during a period corresponding to an unusual number of main breaks, potentially resulting in distribution system contamination.

Indicator of Distribution System Contamination

Due to their high numbers in sewage and sewage-contaminated waters, somatic coliphage may be relatively good indicators of fecal contamination (Hilton and Stotzky, 1973; Havelaar et al., 1991). Somatic coliphage can indicate both animal and human fecal matter (Havelaar et al., 1993). However, other studies have indicated that somatic coliphage are not a reliable indicator of fecal contamination. Leclerc et al. (2000) indicate in a literature review that somatic coliphage may not be specific to *E. coli* and may multiply in the environment. Leclerc et al. (2000) also indicate that it is possible to find somatic coliphages without the presence of fecal contamination. Reali et al. (1991) reviewed the phage literature and reported that most investigators found no correlation between the density of fecal coliform bacteria and the presence of coliphage. Further, LeChevallier et al. (2006) detected a coliphage serotype that was not associated with human fecal contamination, and suggests that more research is needed to determine whether coliphages are an appropriate indicator of distribution system contamination.

Indicator of Public Health Risk

Leclerc et al. (2000) indicates that somatic coliphage may be found in conditions unrelated to presence of a health risk. Enteric viruses have been detected in treated drinking water that was negative for bacteriophages (Grabow et al., 2000). In one recent study, 41.2% of pathogen positive samples occurred with no detectable levels of somatic coliphage, while 47.1% of pathogen positive samples contained >25 PFU/100ml, thus indicating no significant correlation between pathogens and somatic coliphages (Lipp et al., 2001). Ho et al. (2003) also found no statistical association between somatic coliphage and human pathogenic viruses in the 68 samples tested.

Advantages

Standardized methods are available for somatic coliphage that allow easy and rapid detection in environmental samples (Grabow, 1996). Somatic coliphage are also typically present in high numbers in sewage and sewage contaminated waters (Grabow, 1996). In addition, there are circumstances when coliphages may survive in the water environment when indicator bacteria do not (Leclerc et al., 2000). Lastly, coliphages are more resistant to chloramination than to free chlorine, which may therefore make them particularly well suited for use as indicators in chloraminated systems (LeChevallier et al., 2006).

Disadvantages

There is no direct correlation between numbers of phages and viruses in human feces (USEPA, 2000b). Enteric viruses have been detected in water environments in the absence of coliphages, and some coliphages may replicate in water environments (Stevens et al., 2001; Havelaar et al., 1991). Not all infected individuals shed somatic coliphage (Deborde, 1998). The analytical method is more complicated and expensive than traditional bacterial indicators and is not widely used. As indicated above, Leclerc et al. (2000) suggests that somatic coliphage can be found in conditions without presence of fecal contamination or a health risk.

6.1.9 Male-Specific Coliphage

Background

Male-specific coliphages are also referred to as F+ or F-specific coliphage and are viruses that infect *E. coli* through the F-pilus of male strains. The F-pilus allows for transfer of nucleic acid from one bacterium to another. These phage adsorb to F-pili as the first stage of infection and some are relatively resistant to disinfectants. F-specific RNA coliphage exist in four serogroups identified I, II, III, and IV. Groups II and III predominate in humans while Groups I and IV are found in animals (Hsu et al., 1995). According to LeChevallier et al. (2006), Male-specific coliphages infect only *E. coli*. However, LeClerc, et al., (2000) disagree, indicating that they may attack and multiply in other coliforms and *Enterobacteriaceae.*

F-specific phage meet the criteria for pollution indicators by being detectable when pathogens are present, occurring in higher numbers than the pathogen and they are more resistant to environmental influences than pathogens (Lewis, 1995). Woody and Cliver (1995) determined the minimum temperature for replication of F-RNA phage to be 25 degrees C. F-specific RNA phage occur at 10^6/L in sewage (Turner and Lewis, 1995).

Indicator of Breaches of Distribution System Integrity

The presences of male-specific coliphage may be used to indicate a distribution system integrity problem. LeChevallier et al. (2006) detected male-specific coliphage in 5.6 % of 393 distribution system samples. Of those samples that were positive for the presence of male-specific coliphage, more than 77% of the samples were collected within 72 hours of a main break event in the distribution system. Additionally, in the week before a positive coliphage result, between 2 and 13 main breaks occurred, suggesting that the contamination may have come from multiple locations. These results suggest that male-specific coliphage may be effective indicators of distribution system integrity, and main breaks in particular.

Indicator of Distribution System Contamination

Due to their high numbers in sewage and sewage-contaminated waters, male-specific coliphage may be used to indicate the fecal contamination of distribution systems. Type III F-specific coliphage were found to correlate reliably with the release of human fecal contamination, but more research is necessary to be able to track the contamination back to its source (Brion, 2002). All of the isolated coliphage in LeChevallier et al. (2006) were determined to be serogroup I, which is not associated with human fecal pollution; the authors suggest that more studies are necessary to assess whether male-specific coliphage are potential indicators for human fecal contamination of distribution systems.

Indicator of Public Health Risk

Havelaar et al. (1993) found male-specific coliphages were highly correlated with entero- and enteric viruses in multiple environments, including chlorinated effluent waters and UV-irradiated effluent waters.

Advantages

Standardized methods are available for their recovery from drinking water and they have a narrow host range compared with somatic coliphage. F-RNA phage may be good surrogates for enteroviruses because they are of similar size and type (Handzel et al., 1993). Male-specific coliphage are somewhat resistant to disinfectants, and because they are relatively hardier and persist longer, they more closely mirror the behavior of enteric viruses than do bacterial indicators (Havelaar et al., 1990, 1991, 1993; Sobsey et al., 1995). LeChevallier et al. (2006) points out that coliphages may be a better indicator for chloraminated systems than chlorinated systems due to greater resistance to chloramination.

Male-specific coliphage correlate better with presence of pathogens in human feces than somatic coliphage, since somatic coliphage may amplify in the environment (USEPA, 2000b; Havelaar et al., 1991). According to Leclerc et al. (2002), bacteriophage levels, including male-specific coliphage, may also be sensitive to temperature conditions (Leclerc et al., 2000) and bacteriophages may be unlikely to reproduce at the temperatures seen in potable distribution system water.

Disadvantages

Enteric viruses have been detected in water environments in the absence of coliphages (Stevens et al., 2001). A small percentage of people shed male-specific coliphage and they are typically shed in fewer numbers than somatic coliphage. It has been reported that only 3% of humans carry these phages in their *E. coli* (Leclerc et al., 2000).

With respect to using bacteriophages in general as an indicator of enteric viruses, Leclerc et al. (2000) point out the following concerns:

- Production of reproducible results
- Sample volume
- Lack of clear correlation between levels of male-specific bacteriophages in

human feces and that of sewage.
- Methods for enumerating male-specific phages are not accessible, due to complexity, amount of time required, and lack of reproducibility.

Male-specific bacteriophages may not be specific to *E. coli*. and may multiply in *Enterobacteriaceae,* a microbe associated with vegetation and biofilms, and other members of the total coliform group (Leclerc et al., 2000).

6.1.10 Clostridium perfringens

Background

Clostridium spp. are sulfite-reducing, anaerobic, spore-forming bacteria that inhabit the intestinal tracts of humans and animals and are present in sewage and in soil or water that has been fecally contaminated. *Clostridium perfringens* is exclusively of fecal origin and has been recommended by several investigators as a sensitive indicator of sewage pollution of ambient waters (Emerson and Cabelli, 1982; Sorensen et al., 1989; Hill et al., 1993).

Payment and Franco (1993) studied *C. perfringens* as an indicator of treatment efficacy of drinking water for virus removal. Statistically significant correlation was found between *C. perfringens* counts and those of enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts. WHO (2003b) does not recommend Clostridia for distribution system routine monitoring because, due to their length of survival they may be detected long after (and far from) the pollution event, leading to possible false alarms.

Indicator of Breaches of Distribution System Integrity

As for other indicators of fecal pollution, the presence of *C. perfringens* may be used to indicate a distribution system integrity problem, but their presence must be interpreted with caution due to the environmental longevity and resistance of spores. Also, concentrations are much lower than total coliforms and heterotrophic bacteria counts.

Indicator of Distribution System Contamination

As is the case with indicating distribution system integrity problems, *C. perfringens*, may be used to indicate the fecal contamination of distribution systems due to their high numbers in sewage and sewage-contaminated waters, but their presence must be interpreted with caution due to the environmental longevity and resistance of spores. Fujioka and Shizumura (1985) suggested that levels of *C. perfringens* above 50 CFU/100ml were indicative of human fecal pollution. However, there is some concern that *C. perfringens* may not be present in every instance of fecal contamination (USEPA, 1996).

Advantages

C. perfringens is a definitive fecal indicator and standardized methods are available for its rapid and reliable recovery from water. *C. perfringens* was found to correlate statistically with concentrations of enteric viruses and presence of *Giardia* cysts in filtered drinking water (Payment and Franco, 1993).

Disadvantages

Because their spores persist for long periods in the environment, *C. perfringens* can result in false positives and may be less suitable as an indicator of recent fecal contamination. The analytical method requires anaerobic incubation, making the method somewhat more complex than coliform methods.

6.1.11 *Bacteroides fragilis* phages

Background

Bacteroides represent the most abundant bacteria in the gut. Bacteroides are obligate anaerobes of human fecal origin that cannot multiply in the aqueous environment and that die off relatively quickly because oxygen kills them. Bacteriophage of *Bacteroides fragilis* are viruses that infect *B. fragilis* and two in particular may be useful as drinking water quality indicators. The phage to *B. fragilis* HSP40 are found only in human feces and have not been isolated from feces of animals (Havelaar et al., 1991; WHO, 2003c, WHO 2004). However, *B. fragilis* RY2056 phage are more numerous and are not human-specific (Puig et al., 1999).

B. fragilis phage have been determined to be relatively resistant to environmental conditions. Bosch et al. (1989) reported that *B. fragilis* phage were more resistant to chlorine than *E. coli* or polioviruses. According to WHO (2004), one phage in the group *B. fragilis* HSP40, B40-8, has been found to be more resistant to chlorine disinfection than polio virus Type 1, Simian rotavirus SA11, coliphage f2, *E. coli*, and *streptococcus faecalis*. This phage is considered to be typical of the *B. fragilis* HSP40 group.

Jofre et al. (1995) evaluated somatic coliphage, F-specific coliphage and *B. fragilis* phage as indicators of treatment efficacy in drinking water treatment plants. They reported *B. fragilis* phage were not as numerous as coliphage in raw water but they were present in higher numbers than enteroviruses, and they were more resistant to treatment than coliphage, making them better indicators for enteric virus removal in drinking water treatment. However, due to these low numbers, it is possible that the absence of *B. fragilis* phage does not confirm the absence of contamination. WHO 2004 recommends using the *B. fragilis* phage in laboratory investigations, pilot trials, and possibly validation testing. WHO guidelines (2004) recommend against *B. fragilis* phage for operational or surveillance monitoring.

Indicator of Breaches of Distribution System Integrity

Information is lacking regarding whether the *B. fragilis* phage can reliably be used as an indicator that distribution system integrity has been breached.

Indicator of Distribution System Contamination

Recently, bacteriophage of *B. fragilis* have received attention as indicators of human fecal contamination. *B. fragilis* HSP40 phage had been detected in waters receiving human fecal discharges at concentrations up to 5.3×10^5 PFU/100 mL (Tartera et al., 1989). *B. fragilis* phage are present in lower numbers than coliphage, but their presence is a reliable indication of human fecal contamination as it is unlikely that the host organism occurs naturally in the environment (Jofre et al., 1986; Tartera and Jofre, 1987; Araujo et al., 1997).

B. fragilis phages were also found to be reliable indicators of enterovius (Gantzer at al., 1998). More studies are needed to determine whether the *B. fragilis* phage is also an indicator of human fecal and enteric virus contamination (Leclerc et al. 2000). .

Advantages

Bacteroides fragilis phage does not grow in the environment, is predictive of very recent human fecal contamination, and is shed in very high numbers in stools. In addition, *B. fragilis* phages seem to be specific indicators of human fecal contamination as they do not occur naturally in the environment, whereas somatic coliphages and male-specific phages may be indicative of either human or animal fecal contamination (Gantzer et al., 1998). *B. fragilis* phages are the most persistent of the phage indicators and their size and survival rate in the environment are most similar to those of enteroviruses (Contreras-Coll, et al., 2002; Gantzer et al., 1998). *Bacteroides fragilis* HSP40 phage does not replicate in the environment and is an indicator of human fecal pollution.

Disadvantages

Complex analytical methods are required for recovery of *Bacteroides* and *B. fragilis* phage (Contreras-Coll, et al., 2002). The concentration of *B. fragilis* phage in water is significantly less than coliphage. The absence of *B. fragilis* phage does not provide evidence of the absence of fecal contamination.

6.2 Chemical Indicators

6.2.1 Residual Disinfectant

Background

Two federal regulations specify requirements regarding disinfectant residuals in distribution systems. The SWTR requires surface water systems and systems that use ground water under the direct influence of surface water to maintain detectable disinfectant residuals throughout their distribution systems (40 CFR Section 141.72). These systems are required to monitor their disinfectant residuals at the same locations where coliform samples are collected for compliance with the TCR. The Stage 1 Disinfectants/Disinfection Byproducts Rule requires water systems that disinfect to comply with a Maximum Residual Disinfectant Level (MRDL) of 4.0 mg/L as a running annual average in their distribution systems if they are maintaining a residual using either chlorine or chloramines. The required monitoring for MRDL compliance is the same as the required monitoring for SWTR compliance.

Additional information on the effectiveness of disinfectant residuals as indicators of contamination is provided in a white paper currently under development entitled “The Effectiveness of Disinfectant Residuals”.

Indicator of Breaches of Distribution System Integrity

A decrease in disinfectant residual in the distribution system can indicate a contamination problem linked to distribution system integrity. Haas (1999) contended that in some cases, reductions in the disinfectant residual can signify the existence of a contamination problem in the distribution system, including problems resulting from cross-connections and backflow. An EPA Water Protection Task Force (USEPA, 2001) recently suggested that water systems increase the frequency and locations of disinfectant residual monitoring in their distribution systems to ensure proper residuals at all points in the system and to establish a baseline and normal fluctuation from the baseline. The Task Force stated that strategically placed residual monitors are an effective way to alert the system to an unexpected increase in disinfectant demand and, possibly, a breach or contamination of the distribution system.

Disinfectant residuals are likely to be overwhelmed by large contamination episodes such as a substantial sewage backflow event (LeChevallier, 1999). But other breaches of distribution system integrity, such as those associated with pressure transients, can result in smaller amounts of contamination that may not exert a significant disinfectant demand.

Long hydraulic residence times in storage tanks, while not a breach in distribution system integrity, can have a detrimental impact on water quality (USEPA, 2004a). Gauthier et al. (2000) attributed one storage tank’s long turnover rate, which ranged from 5.6 to 7.6 days, as the likely reason for periodic losses in disinfectant residual in the surrounding distribution system.

Biofilms can exert a chlorine demand that reduces the level of disinfectant in the water (Berger et al., 2000). Increased chlorine demand may signal growth of biofilms in portions of the distribution system, and a corresponding reduction in chlorine residual can serve as an indicator of potential biofilm problems.

The kinetics of most chloramine reactions are slower than the kinetics of chlorine reactions (Faust and Aly, 1998). Chlorine that is bound to an ammonia structure in a chloramine compound is less available to react with other chemicals in the water than are its free chlorine counterparts, hypochlorous acid and hypochlorite ion (Hazen and Sawyer, 1992). As a result, chloramines are less likely to display as much variability in their concentrations as chlorine. This accounts for why Snead et al. (1980) stated that chloramine residuals do not show the sensitivity that chlorine residuals do, and therefore are not as effective indicators of distribution system contamination.

Indicator of Distribution System Contamination

Snead et al. (1980) suggested using disinfectant residual as an indicator of distribution system contamination. A sudden change in residual, whether an increase or a decrease, may signal a mechanical failure of the feed system. A decrease may indicate that contamination of the system has occurred as the result of a main break, backflow event, or some other form of distribution system upset that exerted an increased disinfectant demand. The authors clarify that chlorine residual can serve as an effective indicator of distribution system upset for water systems that do not usually have trouble maintaining a residual and do not normally see substantial fluctuations in chlorine demand. They also note that combined chlorine residuals do not function as well in this role, since they are slower to react with contaminants entering the distribution system water.

Denver Water successfully used on-line chlorine residual monitoring in the distribution system to identify the impact of runoff after a forest fire on finished water quality (Kirmeyer et al., 2002a). High dissolved manganese levels in silt washed into a reservoir after the fire, and exerted a chlorine demand in the distribution system. Chlorine residuals continued to decrease as the water moved further through the distribution system.

Indicator of Public Health Outcome

Craun and Calderon (2001) estimated that 14.6 percent of waterborne disease outbreaks that occurred from 1971 to 1998 in community water systems were due to inadequate or interrupted disinfection of ground water. They also estimate that 21.4 percent of the outbreaks during the same time period were due to inadequate disinfection of unfiltered surface water. The authors do not distinguish between outbreaks where primary disinfection of the source was inadequate and those where residual disinfection in the distribution system was inadequate. Therefore, one cannot conclude from these results whether the absence of a disinfectant residual indicated the waterborne disease outbreaks.

The use of disinfectant residual monitoring as an indicator of waterborne disease, has not been entirely reliable, especially when the disease has resulted from contamination due to treatment breakthrough. The clearest examples of this were the *Cryptosporidium* outbreaks in Georgia (Hayes et al., 1989), Oregon (Leland et al., 1993), and Milwaukee (MacKenzie et al., 1994), during which chlorine residuals were maintained throughout the distribution systems that were delivering the contaminated water. Thus, the contamination events did not pose a noticeable disinfectant demand within the distribution system.

While evidence exists supporting the role a disinfectant residual can play in preventing waterborne disease, no documented cases could be found where a reduction in disinfectant residual alerted water system operators or health officials to a waterborne disease outbreak.

Advantages

There are numerous advantages to using disinfectant residual as an indicator of distribution system contamination. Analysis is inexpensive, EPA-approved analytical methods exist, and the results can be reviewed immediately if the system possesses a colorimeter, digital chlorine analyzer, or on-line chlorine analyzer within the distribution system.

Shifts in the disinfectant residual can indicate a wide range of potential issues regarding distribution system contamination, such as cross-connections (Haas, 1999), backflow events (Haas, 1999), and long hydraulic residence times in storage tanks (Gauthier et al. 2000). Changes in the disinfectant residual can also indicate biofilm growth and a vulnerability to waterborne disease outbreaks (Berger et al., 2000).

Disadvantages

Some contamination events can occur over a period of seconds, minutes, or hours, the effectiveness of disinfectant residual measurements as indicators of contamination may depend on the frequency of the residual measurements. Grab sampling may not occur frequently enough for residual measurements to show increases in disinfectant demand resulting from certain types of short-term contamination events.

In order to use disinfectant residual as an indicator of altered water quality, an historical record is necessary to establish the range of residual values that would represent normal functions (in absence of contamination events or breaches of the distribution system), referred to as the baseline. New water systems and systems that have changed their source or treatment method need time to develop such a residual record and historical understanding. Because no documented cases could be found where a reduction in disinfectant residual alerted water system operators or health officials to a waterborne disease outbreak, disinfectant residual may be an unreliable indicator. It also does not identify any single contaminant pathway.

6.2.2 pH

Background

Monitoring for pH is one of the most common tests conducted for water (Addy et al. 2004). In its *Response Protocol Toolbox: Planning for and Responding to Drinking Water Contamination Threats and Incidents* (USEPA, 2003), EPA recommends pH monitoring to establish baseline water quality in the distribution system. In well-buffered waters, pH should remain fairly constant throughout the distribution system, as long as the water has come into equilibrium with the pipes and there are no significant corrosion problems (AWWA, 1999a).

The Lead and Copper Rule (LCR) requires monitoring of pH as part of water quality parameter monitoring in the event the lead or copper action level is exceeded (40 CFR Section 141.87). As part of the corrosion control treatment plan, pH must also be monitored and a minimum pH of 7.0 must be maintained within the distribution system (40 CFR Section 141.82(f)).

Indicator of Breaches of Distribution System Integrity

Changes in the pH can be a direct result of distribution system contamination. Distribution systems have been contaminated with sodium hydroxide as a result of unprotected cross-connections. One case involved backflow following a pressure reduction due to a main break. During the main break, a truck driver was filling a tanker containing sodium hydroxide with water (AWWA PNWS, 1995).

Low pH in soft water may be indicative of the leaching of some metals and organic chemicals from pipes such as lead, arsenic, and cadmium (USEPA, 2004b). In cement-lined pipes or tanks, an increase in pH over time can be indicative of leaching (Kirmeyer et al., 2002b).

An increase or decrease in the pH of the distributed water will affect corrosion and can therefore be an indicator of potential corrosion problems. Corrosion control efforts may be less effective due to decreases in pH. The pH of water in the distribution system is an important factor in nitrification activity (Harrington et al., 2003). First, a reduction of total alkalinity may accompany nitrification because a significant amount of bicarbonate is consumed in the conversion of ammonia to nitrite. While reduction in alkalinity does not impose a direct public health impact, reductions in alkalinity can cause reductions in buffering capacity, which can impact pH stability and corrosivity of the water toward lead and copper. Thus pH as an indicator can be used along with alkalinity as an indicator of nitrification.

A reduction in pH can be an indication of problematic biofilm growth. For example, a decrease in pH can result from growth of sulfur-reducing bacteria such as *Thiobacillus*. These bacteria generate hydrogen ions which lowers the pH (AWWA, 1995). A growth in nitrifying bacteria may also decrease the pH by oxidizing ammonium to nitrate and other nitrogen compounds (Schock, 1999).

Indicator of Distribution System Contamination

After establishing a baseline for the pH of the water, a change in pH can be an indication of some contamination events (Kirmeyer et al., 2002b).

Advantages

pH is a commonly-monitored parameter, although monitoring is not necessarily required under all circumstances. The concept of pH is understood by most operators of distribution systems, and equipment is often already available. The pH can be monitored using on-line monitoring equipment, by doing grab samples in the field, and in a water treatment plant laboratory, allowing for almost immediate results.

Disadvantages

A change in pH does not indicate what specific type of contamination event may have occurred. The change in pH may be minimized by highly buffered water. The equipment needed to measure pH must be routinely maintained and calibrated. If not already available, continuous monitoring equipment may be relatively expensive, depending upon the number of sites monitored.

6.2.3 Alkalinity

Background

Alkalinity, composed mostly of carbonate and bicarbonate ions, is a measure of the ability of a water to neutralize acids and bases (AWWA, 1999a).The LCR requires monitoring of alkalinity as part of water quality parameter monitoring in the event the lead or copper action level is exceeded (40 CFR 141.87).

Indicator of Breaches of Distribution System Integrity

Alkalinity can be used to evaluate pipe replacement or storage tank coating rehabilitation needs (Kirmeyer et al., 2002b). Cement-lined pipes and storage tanks can leach calcium carbonate into the water, which may significantly increase the alkalinity of the water. This is especially true when the cement-lined material is new, but also depends on the type of cement used, the contact time between the water and cement material, and the diameter of the pipe (Friedman et al., 2002).

Alkalinity can be used as an indicator to determine the corrosivity of water in the distribution system. For example, leaching from metal pipes most commonly occurs in low alkalinity waters. In addition, a reduction in alkalinity results in a reduction of the buffering capacity of the water. Without buffering, the pH can more easily fluctuate, which may lead to corrosive conditions.

Advantages

The method for analyzing alkalinity is well established. Alkalinity testing is inexpensive and analytical results can be obtained quickly. Water system operators can perform testing on-site.

Disadvantages

A change in alkalinity does not indicate presence of specific contaminants, but it does indicate there has been a water quality change that may be associated with or cause an increase in corrosion or biofilm occurrences (e.g., pH). In addition, current monitoring for alkalinity under existing rules such as the LCR is limited in its scope in terms of both frequency and location. Using alkalinity as an indicator would require the establishment of a baseline condition first, and may require more frequent samples that are more broadly representative of potential problem areas in the distribution system.

6.2.4 Calcium

Background

Water hardness is attributed to the presence of calcium and magnesium ions. Hard water is generally less corrosive than soft water due to increased concentrations of calcium in the hard water. Depending on the water’s pH and alkalinity concentration, calcium will combine with carbonate alkalinity to form a protective coating on the pipe wall that can retard corrosion (AWWA 2000). Waters low in calcium (soft waters), pH and alkalinity can result in corrosive conditions affecting cement-lined pipes and storage tanks. Rather than calcium concentration itself, an increase or decrease in calcium concentration may indicate potential for contamination to be released in the distribution system. The LCR requires monitoring of calcium as part of water quality parameter monitoring in the event the lead or copper action level is exceeded (40 CFR Section 141.87).

Indicator of Breaches of Distribution System Integrity

Increased concentrations of calcium in the distribution system can be an indication of corrosion in cement-lined pipe or storage tanks. Cement-lined pipes and storage tanks can leach calcium carbonate into the water. This is especially true when the cement-lined material is new, but also depends on the type of cement used, the contact time between the water and cement material, and the diameter of the pipe. Monitoring must be conducted in the finished water in order to observe changes in calcium levels.

Waters that have very low ion content (soft waters) are aggressive to calcium hydroxide contained in hydrated cements (ACIPCO, 2002). Calcium hydroxide will also leach from cement-mortar linings exposed to soft waters (Friedman et al., 2002). The extent of leaching increases with, among other factors, the residence time in the pipe and is inversely proportional to the pipe diameter. A decrease in calcium levels could indicate the potential for increased scale formation and reduced flow.

Advantages

The methods for analyzing calcium are well established. Calcium testing is both inexpensive and analytical results can be obtained quickly (Skipton et al., 2004).

Disadvantages

Calcium is not a specific indicator for contaminants. Detection of increased levels of calcium above finished water levels may indicate corrosion of cement-lined pipes or it could also indicate resolubilization of calcium carbonate pipe coating, developed as part of a corrosion control strategy. More information and other indicators would be necessary to identify the specific problem.

6.2.5 Conductivity

Background

Conductivity, or specific conductance, is a measure of the ability of water to carry an electric current (APHA, 1995). This ability depends on the concentration, mobility, and valence of ions in the water as well as on water temperature. In general, water containing substantial concentrations of inorganic compounds has higher conductivity. Water containing organic molecules that do not dissociate well will have lower conductivity. The conductivity of potable water in the United States usually falls within the range of 50 to 1500 μmhos/cm (APHA, 1995), which is the typical range of fluctuation within systems.

Conductivity can be analyzed by the water system (if the system possesses the necessary equipment) or analyzed by a laboratory for about $10 (Energy Laboratories, 2003).

The LCR requires monitoring of conductivity as part of water quality parameter monitoring in the event the lead or copper action level is exceeded (40 CFR Section 141.87).

Indicator of Breaches of Distribution System Integrity

Kirmeyer et al. (2001) list conductivity as one of the test parameters for water systems to watch, because a sudden increase or decrease in conductivity often accompanies a distribution system pathway breach or contamination event.

Conductivity will remain fairly constant throughout a distribution system as long as the water is in equilibrium with the pipe material. Conductivity may vary more if there are corrosion problems (USEPA, 2003). Thus changes in conductivity may indicate corrosion problems.

Indicator of Distribution System Contamination

Conductivity is one of the water quality parameters that EPA recommends water systems consider for establishing a baseline for their distribution systems' water quality for security purposes (USEPA, 2003). By doing so, systems will then know what is typical for their water, and any excursions outside the normal range of measurements can serve as an indicator of a potential contamination threat.

Advantages

Conductivity measurements can be made frequently at low cost. Measurements can be made using continuous on-line meters, or with portable instruments. If the system possesses the necessary instruments, conductivity results can be obtained immediately.

Disadvantages

Conductivity provides an estimate of the ionic strength of water. It does not provide specific information about the composition of the ions or microbial contaminants in the water. Additional water chemistry analysis needs to be performed for a water system to follow up on a sudden shift in conductivity.

6.2.6 Fecal Sterols

Background

Fecal sterols are metabolites of cholesterol that are found in the gut and feces of humans and animals. Coprostanol is a fecal sterol that is commonly found in domestic wastewater. A study by Leeming et al. (1996) showed that coprostanol constitutes approximately 60 percent of the total sterols found in human feces. The researchers also found coprostanol in cat and pig feces, but at concentrations approximately 10 times lower than in human feces. Fecal sterols other than coprostanol were found to be predominant in other animals including cows, horses, and sheep. Thus, coprostanol could be used to distinguish between fecal contamination from humans and animals (Leeming et al., 1996). A Standard Method or EPA Method does not exist for the analysis of fecal sterols. Detection of fecal sterols at the levels present in wastewaters requires gas chromatography-mass spectrometry. The detection limit of the gas chromatography-mass spectrometry method for detecting fecal sterols is estimated to be 10 to 50 nanograms per liter when a 1-liter sample is analyzed (Gomez et al., 1998).

Indicator of Distribution System Contamination

Coprostanol was first studied as an indicator of fecal pollution by Kirchmer (1971). A comprehensive review of coprostanol as an indicator of fecal pollution was published by Walker et al. (1982). Since then, papers on fecal sterols as indicators of sewage and sewage sludge in coastal waters (Chan et al., 1998; Eaganhouse et al. 1988), discuss the relationship between fecal sterols and fecal indicator bacteria (Leeming and Nichols, 1996; Nichols et al., 1993), and the use of fecal sterols to determine the source of fecal pollution (Leeming et al., 1996), have focused attention on this chemical alternative to microbial fecal indicators. No published studies examining the presence of fecal sterols in treated drinking water have been identified.

Isobe et al. (2004) found a parallel logarithmic correlation between *E. coli* and coprostanol for measuring fecal contamination of surface water; however the method has not been applied to distribution system monitoring because the method may not be sensitive enough to detect the low levels of coprostanol in drinking water (Gomez et al., 1998).

No information or studies were identified specifically on fecal sterols as potential indicators in drinking water systems.

Advantages

An advantage of using fecal sterols as an indicator is that they may allow differentiation between human sewage pollution and fecal contamination from animals.

Disadvantages

The gas chromatography-mass spectrometry analytical method is expensive, complex, and many drinking water treatment facilities do not have the necessary equipment or training to run the analysis. Fecal sterols do not indicate non-fecal contamination. It is not known if fecal sterols are present in source water or how effectively they are removed in water treatment processes. Thus, it would be difficult to establish a baseline for making a distinction between source or distribution system contamination, such as through a cross-connection.

6.2.7 Caffeine and Pharmaceuticals

Background

Caffeine and pharmaceuticals are discharged into the aqueous environment in wastewater, and they serve as source tracking indicators of human sewage pollution. Their presence in groundwater suggests a possibility of septic or sewage contamination. Their concentration in treated drinking water seldom exceeds the detection limit of available analytical methods (Kolpin et al., 2002). A Standard Method or EPA Method does not currently exist for caffeine or pharmaceuticals.

Kolpin et al. (2002) conducted a national survey of pharmaceuticals, hormones, and other organic wastewater contaminants (OWCs) in 139 streams in 30 states during 1999-2000. The selection of sampling sites was biased toward streams susceptible to contamination (i.e., downstream of intense urbanization and livestock production). OWCs were prevalent during this study, as they were found in 80 percent of the streams sampled. The compounds detected represent a wide range of residential, industrial, and agricultural origins and uses. The most frequently detected compounds were coprostanol (fecal steroid), cholesterol (plant and animal steroid), N,N-diethyltoluamide (insect repellant), caffeine (stimulant), triclosan (antimicrobial disinfectant), tri(2-chloroethyl), phosphate (fire retardant), and 4-nonylphenol (nonionic detergent metabolite). Measured concentrations for this study were generally low and rarely exceeded drinking water guidelines, drinking-water health advisories or aquatic-life criteria.

Indicator of Distribution System Contamination

Caffeine and pharmaceuticals are excreted in urine and are present in sewage effluents as a marker of human sewage pollution (Standley et al., 2000; Siegener and Chen, 2002). Buerge et al. (2003) reported caffeine concentrations ranging between 7-73 μg/L in wastewater influents, and concentrations of 0.03-9.5 μg/L in effluents of wastewater treatment plants, which amounts to 81-99 percent removal. Ambient concentrations of caffeine in lakes and rivers ranged from 6-250 nanograms (ng)/L. Remote mountain lakes contained < 2 ng/L caffeine, suggesting caffeine may be useful as a marker of human impact upon the environment (Buerge et al., 2003).

Weigel et al. (2002) surveyed the occurrence of drugs and personal care products as pollutants in the North Sea. Analyses were conducted for clofibric acid (reduces cholesterol levels in blood), diclofenac (anti-inflammatory), ibuprofen (anti-inflammatory), ketoprofen (anti-inflammatory), propyphenazone (pain reliever), caffeine, and N,N-diethyl-3-toluamide (DEET) (insect repellant). Clofibric acid, caffeine, and DEET were present throughout the North Sea in concentrations of up to 1.3, 16 and 1.1 ng/L, respectively. Diclofenac and ibuprofen were found in the estuary of the river Elbe (6.2 and 0.6 ng/L, respectively) but in none of the marine samples. Ketoprofen was below the detection limit in all samples.

Few studies were identified linking caffeine to drinking water. Seiler et al. (1999) surveyed groundwater from private and public wells, together with monitoring wells around Reno, NV for nitrate, caffeine, and pharmaceuticals to evaluate their presence and relationship to wastewater contamination. Results of this study indicate that these compounds can be used as indicators of recharge from domestic wastewater, although their usefulness is limited because caffeine is reactive and can break down in the environment and the presence of prescription pharmaceuticals is unpredictable. Caffeine was detected in ground water samples at concentrations up to 0.23 μg/L (Seiler et al. 1999). The human pharmaceuticals chlorpropamide, phensuximide, and carbamazepine also were detected in some samples.

Advantages

The concentration of caffeine in treated drinking water seldom exceeds the detection limit of available analytical methods (Kolpin et al., 2002), whereas the concentration in wastewater is typically much higher, thus a wastewater contamination event may result in a significantly higher level, that is detectable over baseline. Since most pharmaceuticals are not naturally occurring, the presence of pharmaceuticals is a clear link to human-caused pollution.

Disadvantages

Detection of caffeine at the levels present in source waters and wastewaters requires liquid chromatography-mass spectrometry. Detection of pharmaceuticals requires liquid chromatography-mass spectrometry. These are expensive and complex methods and many drinking water treatment facilities do not have the necessary equipment or training to run the analysis. Analysis of a single sample for caffeine by an independent laboratory may cost as much as $435 with a 7 to 14 day turnaround (Source Molecular Corporation, 2002).

Another disadvantage of caffeine and pharmaceuticals as indicators is that caffeine is reactive and can break down in the environment and the presence of prescription pharmaceuticals is unpredictable. Soil microbes easily degrade caffeine. Some plants have significant levels of caffeine, which could confuse results (Hagedorn, 2004).

An additional disadvantage is that it may be difficult to distinguish between presence of caffeine and pharmaceuticals from source water that may or may not be removed by treatment, or whether their presence is related to a distribution system pathway.

6.2.8 Organic Carbon

Background

Most organic carbon in water comes from decaying plant materials present in source waters, and it is present in several measurable forms, including the following:

Total Organic Carbon (TOC) is total organic carbon in mg/L measured using heat, oxygen, ultraviolet irradiation, chemical oxidants, or combinations of these oxidants that convert organic carbon to carbon dioxide, rounded to two significant figures (40 CFR Section 141.2). Most of the organic carbon in drinking water is in the form of dissolved organic carbon (Symons et al., 2000). Typical levels of TOC in drinking water derived from surface source waters range from 1-20 mg/L, while ground water has a range of 0.1-2 mg/L. From the standpoint of measuring nutrients that can stimulate bacterial growth in the distribution system, total organic carbon is not as applicable as AOC and/or BDOC (LeChevallier, 1991).

Dissolved Organic Carbon (DOC) is the portion of organic carbon in water that passes through a 0.45-micron pore-diameter filter (Symons, et al., 2000).

Biodegradable Organic Carbon (BDOC) is a measure of the fraction of the organic carbon in water that can be mineralized by heterotrophic microorganisms (Huck, 1990). Kirmeyer et al. (2002b) present a cost for BDOC analysis of $200. There is currently no Standard Method for BDOC.

Assimilable Organic Carbon (AOC) is a measure of the fraction of dissolved organic material in the water that can be used as a carbon and energy source by microorganisms (Symons et al., 2000). LeChevallier (2001) reported AOC levels in North American drinking water from 0.020 to 0.214 mg/L. The analytical costs for AOC at a laboratory can be as high as $450 (Hoosier Microbiological Laboratory, 2001, Muncie, Indiana) and only a few laboratories were located that were capable of performing this analysis. Standard Method 9217B can be used to analyze AOC concentrations in a water sample. Camper et al. (2000) recommended that utilities monitor both AOC and BDOC because both types of compounds can be consumed by microorganisms.

Indicator of Breaches of Distribution System Integrity

The use of nonmicrobial indicators, such as AOC and BDOC, provides a means of characterizing the potential for microbial growth. The level of AOC entering the distribution system and within the distribution system may control the rate and extent of biofilm development (USEPA, 2002). AOC was first proposed as a means of determining the nutrient potential of water (van der Kooij et al., 1984). Van der Kooij (1992) related the presence of AOC with growth of bacteria in distribution system water. AOC increased with increasing distance from the treatment plant and the number of heterotrophic bacteria was directly related to temperature and AOC. Coliform growth typically requires AOC concentrations greater than 0.05 mg/L (LeChevallier, 1991; Volk and Joret, 1994).

Limiting the amount of AOC in water has been shown to control the growth of biofilms in the distribution system (Schellart, 1986; van der Kooij, 1992). From a study of 20 types of drinking water, van der Kooij (1992) concluded that AOC concentrations less than 0.01 mg/L of carbon in drinking water entering the distribution system prevent the growth of heterotrophic bacteria.

LeChevallier (2001) reported that among North American drinking water systems, those systems with AOC levels above 0.100 mg/L had 19 times more coliform positive samples than systems with AOC levels below 0.099 mg/L. However, no single factor was determined to be responsible for all coliform occurrences.

Because of the technical problems associated with the AOC method, some investigators prefer a test for BDOC (Huck, 1990). DOC and BDOC analyses are primarily research tools for understanding the metabolic activity occurring in biofilms.

Advantages

An advantage of using AOC and BDOC as an indicator of biofilms is that AOC and BDOC are nutrients for biofilms and have been clearly linked to biofilm growth. Several studies have shown that limiting AOC in treated drinking water limits biofilm growth in the distribution system (Schellart 1986; van der Kooij 1992).

Disadvantages

LeChevallier (2001) concluded that AOC alone may not be an accurate predictor of microbial growth. The cost for AOC analysis is expensive, unless the system has the ability to perform the analysis at its own laboratory. Like the microbial methods, a disadvantage of both the BDOC and AOC tests is that the tests typically require a minimum of 2 or 3 days to obtain results and can take up to 4 weeks.

6.2.9 Adenosine Triphosphate (ATP)

Background

ATP is found in all living microbial cells. It serves as a major energy source within a cell to drive a number of biological processes including protein synthesis, photosynthesis and muscle contraction (Columbia Encyclopedia, 2001). By supplying an energy source, ATP aids organisms in sustaining life. Therefore, the presence of ATP in the distribution system suggests biological activity.

ATP measures metabolic activity of living cells making it a potential microbial indicator. Boe-Hansen et al. (2003) found ATP measurement to be rapid and easy to perform while investigating biofilm growth in a model distribution system. It has a high sensitivity for biomass measurements under low nutrient conditions. There is a highly significant correlation between ATP and Acridine Orange Direct Count (AODC) data (Boe-Hansen et al., 2003). Use of ATP as an indicator of metabolic activity of the biomass in samples or on surfaces is already being performed, particularly in the food industry (Tanaka et al., 1997).

The concentration of ATP, and subsequent change in microbial growth, will vary depending upon the conditions of the water system, such as the treatment type. For example, Chu et al. (2003) determined that average biofilm growth rates were 325 pg ATP/cm^2 for chlorine-free water, 159 pg ATP/cm^2 for low-chlorine water, and 118 pg ATP/cm^2 for high chlorine water. In the Netherlands, Magic-Knezev and van der Kooij (2004) showed that ATP concentrations ranged from 25 to 5000 ng ATP/ cm^3 and varied depending upon the long run filter time and type of filter. Pipe material can also influence biofilm activity, and therefore, the amount of ATP. For example, mean biofilm activity was lowest in glass pipes (136 pg ATP/cm^2), and higher in cement (212 pg ATP/cm^2), MDPE (302 pg ATP/cm^2), and PVC pipes (509 pg ATP/cm^2; Hallam et al. 2001).

In France a new ATP extraction and titration system of bacterial ATP was used during 2001 to test the Paris drinking water. Delahaye et. al (2003) found a linear relationship between log (ATP) and log (HPC-R2A/ml). Furthermore, there was a slight change in the microbiological quality in the Paris network, which was related to the distance traveled from the production location to the site, as well as to a reservoir effect.

Indicator of Breaches of Distribution System Integrity

ATP can be used as an indicator to estimate biomass in the distribution system. Boe-Hansen et al. (2003) selected total microscopic counts AODC HPC, and ATP as indicators of biomass in a model distribution system to measure total biomass, viable biomass, and metabolically active biomass, respectively. Based on the study, they recommended the combination of AODC and ATP as the preferred method of quantitatively estimating biofilm biomass. A standardized method for analyzing ATP in water exists (ASTM D4012-81), but it is not EPA approved.

In the Netherlands, ATP measurements are currently being monitored and used to assess biofilm concentrations in the distribution system, to determine the biofilm growth rate of treated water, and to use as a general indicator of microbial growth (van der Kooij et al., 2003).

In biofilms, the concentration of ATP has been directly correlated with the concentration of *Candida albicans* (Jin et al., 2004), *Legionella pneumophila* (Kuiper et al, 2004), and *Pseudomonas fluorescens* (Simoes et al., 2005). ATP was used as an indicator to determine that *Streptococcus faecalis* and *Escherichia coli* could survive and remain physiologically active in petroleum-contaminated tropical marine waters (Santo Domingo et al., 1989).

Indicator of Distribution System Contamination

Since ATP is used to monitor general levels of bacterial growth, ATP can not be directly correlated to the activity of microbes of fecal origin.

Advantages

ATP has been used successfully in some model and actual distribution systems as a general indicator of biofilms and microbial growth.

Disadvantages

The bioassay method for measuring ATP is a complex method. Rapid, easy methods have been developed for use in the food industry, but their applicability to treated drinking water is not known. There is no EPA approved method for measuring ATP. There is limited application for ATP testing at temperatures less than 10º C or for stressed cells. Interpretation of ATP data may be problematic because the amount of ATP is related to the nutritional state of the organisms, and it is important to ensure that the ATP results correlate with AODC data (Boe-Hansen et al., 2003).

6.2.10 Endotoxin

Background

Endotoxin is the cell wall lipopolysaccharide (LPS) of Gram-negative bacteria. Gram-negative bacteria such as *Pseudomonas* and *Aeromonas* can enter the distribution system and contribute to biofilm formation, which can subsequently protect microbes from disinfection (AWWA, 1999b).

Indicator of Breaches of Distribution System Integrity

Endotoxin could indicate intrusion, backflow, or other events if the intruding matter contains Gram-negative bacteria.

Endotoxin can be used as an indicator for determining the presence of Gram-negative bacteria in the distribution system in suspension or biofilm. However, endotoxin is not a good indicator of biofilm microbial populations, nor of fecal contamination alone, since endotoxin measurements do not discriminate between biofilm and suspension.

- Haas et al. (1983) attempted to use the limulus amoebocyte lysate (LAL) spectrophotometric assay for Gram-negative bacterial endotoxins as a measure of water quality, but was unable to correlate endotoxin results with HPC tests. They concluded that the LAL test held little promise for assessing drinking water quality as there was no relationship between endotoxin results and HPC tests.

- Korsholm and Sogaard (1987) compared HPC to endotoxin concentrations in 229 unchlorinated drinking water samples and found that counts on R2A medium were weakly correlated with LPS concentrations. Use of endotoxin detecting assays to detect trace contamination from Gram-negative bacteria is sensitive but not sufficiently specific for use in drinking water monitoring Korsholm and Sogaard (1987).

Advantages

There is a standardized method available for analyzing endotoxin (ASTM E2250-02). The test method is highly sensitive (Korsholm and Sogaard, 1987). An endotoxin test kit is commercially available for water operators to perform on-site testing.

Disadvantages

There is limited specificity when using endotoxin as an indicator as it only detects Gram-negative bacteria. There is poor correlation between endotoxin measurements and HPCs.

6.2.11 Iron

Background

Metals accumulated in distribution systems, such as iron, can be released to the flowing water during hydraulic disturbances or change in water quality (Reiber et al., 1997a). Metal solubility is strongly affected by the water's alkalinity, pH, and hardness.

Iron is oxidized and reduced by various bacteria, causing corrosion and fouling of pipes. The genera *Gallionella* and *Leptothrix* are particularly associated with "red water" and fouling of domestic water systems (Geldreich, 1996). "Red water" is generally caused by iron corrosion and is common in old unlined cast iron mains or under turbulent conditions (Kirmeyer et al., 2002b). The accumulation of iron in the distribution system can be a result of oxidation and settling of iron (Kirmeyer et al., 2002b).

Iron entering water as a result of corrosion frequently deposits into scales that line pipe walls. These scales provide a location for numerous compounds and corrosion byproducts to accumulate (McNeill and Edwards, 2001). Scale dissolution can return metals into the water either as soluble species or attached to scale particles that have detached from the pipe surface.

The secondary MCL for iron is 0.3 mg/L. Approved methods for iron analysis include EPA Methods 200.7 and 200.9 and Standard Methods 3120B, 3111B, and 3113B.

Indicator of Breaches of Distribution System Integrity

An increase in iron concentrations over time can indicate that corrosion has taken place, and may have affected the structural integrity of the pipe. This can help the system to determine pipe replacement frequency (Kirmeyer et al., 2002b).

Iron can also be monitored at dead ends and if an increase in historical iron levels is noted, the system may use this as a tool to determine flushing frequency (Kirmeyer et al., 2002b). If sequestering is practiced, an increase in iron concentration may indicate that the sequestering agent is not properly working (USEPA, 2004b).

Corrosion can result in the release of contaminants, such as iron, into the distribution system. Unlined cast iron mains have shown to be a source of iron in the distribution system under corrosive water conditions (Friedman et al., 2004a). Iron deposits have shown an increase when the time between flushing of the water mains increases (Friedman et al., 2004a). Iron can also be released from cast iron pipe by aggressive waters (USEPA, 2004b). In some instances, the increase of iron concentrations over time may be indicative of long retention times that allow oxidized iron to settle.

Low flow conditions favor the release of soluble iron from pipe walls (Brandt et al., 2004). The addition of chlorine to previously unchlorinated ground water can affect the composition and stability of scales on pipe, resulting in the release of particulate iron. This condition occurred in Fremont, Nebraska, where iron levels greater than 300 mg/L were obtained when the system initiated chlorination (Reiber et al., 1997b). The release of iron was related to the oxidation by chlorine of ferrous iron bearing corrosion scales in the distribution system.

Flushing of 8-inch mains in Newport News, Virginia, indicated unlined cast iron pipe produced significantly more iron when flushed as compared to lined ductile iron pipe within the same distribution system that received the same finished water (Friedman et al., 2004a). This study indicates corrosion of unlined cast iron pipe provides a significant (91-times more) contribution of iron-rich deposits when compared to lined ductile iron pipe.

Advantages

Iron is a frequent product of corrosion in iron pipes. The presence of high concentrations of iron compared to finished water levels would indicate corrosion and increased concentrations could signify release. The cost of an iron analysis is relatively inexpensive at about $10 per sample. EPA Method 200.8 will also detect the presence of other metals.

Disadvantages

Corrosion byproducts can migrate throughout the distribution system, making it difficult to directly relate the measurement of iron in a sample to a specific problem location (Friedman et al., 2004a)

6.2.12 Ammonia, Nitrate, Nitrite, and Nitrogen

Background

Chloramination is the practice of adding ammonia and chlorine to form chloramines, a more stable disinfectant than free chlorine. Where chloramination is practiced, ammonia may be detected in the distribution system. The ammonia can be attributed to residual ammonia that is added as part of the chloramination process, or to ammonia that is released as part of the decay of chloramines (Harrington, 2003). In some cases, ammonia may be naturally-occurring. In the presence of ammonia, nitrifying bacteria may begin the process of nitrification by using ammonia as an energy source. Ammonia-oxidizing bacteria (AOB) of the genus *Nitrosomonas* can oxidize ammonia to nitrites. Nitrites may then be oxidized to nitrates by bacteria of the genus *Nitrobacter* as the final step in the nitrification process. Where ammonia is found in the distribution system, concentrations of nitrite and nitrate may increase as nitrification occurs in the distribution system.

Indicator of Pathways that Breach Distribution System Integrity

Nitrites may indicate the decomposition of chloramine residual, which has been associated with an increase in heterotrophic bacteria (Harrington, 2003). Measurement of nitrite and nitrate above background levels can indicate a nitrification event. In addition to measuring nitrate, nitrification is often indirectly identified by one or more symptoms including (Wilczak et al., 1996):

- Loss of chloramine residual
- Increase in water temperature
- Decrease in dissolved oxygen
- Drop in pH (emphasis added) and alkalinity
- Increase in HPC population

Monitoring for ammonia in the distribution system can indicate the disinfection efficiency of the chloramination process. Monitoring for these nutrients for optimization of the chloramination process could also serve as an indicator of corrosion and acute cross-connection risks (i.e., sewage and fertilizer wastes) if a sudden increase was noted for these contaminants.

Advantages

Ammonia, nitrites, and nitrates are relatively easy to sample and analyze.

Disadvantages

Analysis costs are modest, depending upon the desired detection level (Energy Laboratories, 2003). However, the expenses associated with labor and analysis costs could become significant over time if optimization of the chloramination process requires continuous monitoring.

6.2.13 Aluminum

Background

Aggressive, soft, and poorly buffered (i.e., low alkalinity) water promotes aluminum leaching from cement materials. These are the same water quality conditions that are conducive to leaching of lead and copper. Aluminum has a secondary MCL between 0.05 mg/L and 0.2 mg/L (40 CFR Section 143.3). Aluminum can be present in the distribution system as a result of chemical feed practices, such as adding alum as a coagulant, or as a result of leaching from pipe materials.

Indicator of Breaches of Distribution System Integrity

An increase in aluminum can be an indicator of corrosive conditions created by problematic biofilms, e.g., sulfur-reducing bacteria and nitrifying bacteria.

An increase in aluminum concentrations within the distribution system can also be an indicator of leaching. Aluminum has been reported to leach from the cement-mortar lining of distribution pipe.

In a study by Berend and Trouwborst (1999), the installation of 7,200 feet of cement-mortar lined ductile iron pipe caused aluminum levels in a water supply to increase from 5 µg/L to 690 µg/L over the course of 2 months. More than 2 years later, aluminum continued to leach from the lining and produce water with over 100 µg/L of aluminum. The water that was being distributed by the pipes in the study was aggressive (maximum Langelier Index between -0.5 and -1.5), soft (hardness 15-20 mg/L as $CaCO_3$), of low alkalinity (no data), and high pH (8.5 to 9.5). The extent of leaching is also strongly related to the contact time between the water and the cement-mortar lining. In the study by Berend and Trouwborst (1999), the average contact time was 2.3 days.

Advantages

Sampling and analysis for aluminum are relatively straightforward and inexpensive (Energy Laboratories, 2003). Sampling in areas of pipe with cement-mortar lining may easily identify leaching of aluminum when compared with aluminum levels in samples taken from the entry point(s).

Disadvantages

Detection of elevated aluminum levels would not identify the source of corrosive conditions per se. Further investigation to identify the cause of corrosive conditions would likely be necessary. If aluminum salts are used as a coagulant in the treatment process, aluminum may also have to be monitored after treatment to establish background levels following treatment. Alum floc may also accumulate in distribution system sediments, further confounding the use of aluminum as an indicator of leaching (NRC, 2006).

6.2.14 Chloride

Background

Chloride is present in agricultural, industrial, and domestic wastewaters that are discharged to surface waters. Home water softeners contribute a significant amount of chlorides as a result of the regeneration process. Human excreta are another significant source of chlorides with an average of about 6 grams of chloride per person per day (Metcalf and Eddy, 1991). The secondary MCL for chloride is 250 mg/L. Methods for detecting chloride in water include Standard Methods 4110B, 4500-Cl$^-$D, and EPA Method 300.0A. The analysis for chloride is relatively inexpensive at approximately $15 per sample (Kirmeyer et al., 2002b).

Indicator of Breaches of Distribution System Integrity

Because chlorides are found in agricultural, industrial, and domestic wastewaters and home water softeners, which are known to be associated with cross connections, chloride presence in the distribution system above background levels may indicate that backflow is occurring through these types of cross connections. Increases in chloride concentrations could also indicate intrusions of brackish water.

Indicator of Distribution System Contamination

Conventional methods of sewage treatment do not significantly remove chlorides. Therefore, detection of higher than normal concentrations of chloride in a body of water may indicate that treated sewage is being discharged into it (Metcalf and Eddy, 1991). Detection of increased chloride concentrations in the distribution system may also indicate contamination by treated or untreated sewage.

Chloride is naturally occurring and can leach into source water from chloride-containing rocks and soils. Chloride can also occur due to salt-water intrusion. Road salt, fertilizer, and landfills are other potential sources of chloride. Therefore, although the presence of increased levels of chloride can indicate contamination, the source of the contamination may not be clear.

Advantages

The analysis for chloride is relatively simple and inexpensive.

Disadvantages

A disadvantage of using chloride as a fecal indicator is that there are multiple potential sources of chloride and therefore the source of chloride contamination may not be clear.

6.2.15 Microbially Available Phosphorous

Background

In general, phosphorus naturally occurs in groundwater or may be added as part of corrosion control treatment. The range of naturally occurring phosphorus can vary widely. Phosphorus has been found to be present at levels as high as 300 µg/L or as low as 0.1 µg/L (Geldreich, 1996). Miettinen et al. (1997a) indicate that most total phosphorus in drinking water sources is associated with particles. In general, the dissolved total phosphorus portion, which is biodegradable, is present in very small amounts. Recent evidence suggests that phosphate concentrations regulate microbial growth in biofilms (Lehtola et al. 1999; Lehtola et al. 2002). Lehtola et al. (1999) developed a method to quantify the amount of phosphorus in drinking water that can be used by microorganisms for growth. Microbially available phosphorus (MAP) can be determined using a bioassay in which the maximum growth of *Pseudomonas fluorescens* P17 is related to the concentration of MAP. Lehtola et al. (1999) found that the mathematical factor relating maximum growth to MAP is 373,200 ± 9,400 CFU per microgram of PO_4-P.

Indicator of Breaches of Distribution System Integrity

In certain environments where phosphorus is the limiting agent, Lehtola et al. (1999) found that even a very low concentration of phosphorus (below 1 µg/L) can promote extensive microbial growth. In later work, Lehtola et al. (2002) found that when chlorine was not removed, there was a correlation between MAP and heterotrophic bacteria growth potential at MAP concentrations less than 2 µg/L. Sang et al. (2003) investigated the influence of PO_4^{3-}-P on bacterial growth in effluent from pilot-scale drinking water treatment. The results demonstrated that phosphorus became the limiting nutrient when AOC was 200 µg C/L and phosphorus was below 4 µg C/L. Increasing phosphorus above this level resulted in corresponding increases in bacterial growth. Thus, in phosphorus-limited environments, the presence of even low levels of phosphorus indicates the potential for microbial growth and increased biofilms.

Advantages

The method for determining MAP was only recently developed and is not yet widely used. Therefore, insufficient information is available to determine the advantages of using MAP as an indicator for biofilms.

Disadvantages

Although an association has been shown between MAP and microbial growth, the critical concentrations and effects are not sufficiently documented to determine a cutoff level to which MAP should be limited.

Another disadvantage of the MAP test is that the test typically requires 4 to 8 days to obtain results. Therefore, changes in MAP are not immediately discernable and the response to such changes is significantly delayed.

6.2.16 Turbidity

Background

Turbidity is a measure of filter efficacy. Current regulations (40 CFR §141.173) require conventional and direct filtration plants treating surface water or ground water under the direct influence of surface water to maintain the turbidity of finished water below 0.3 NTU (in 95 percent of 4-hour monthly readings). Turbidity above this limit suggests filter deficiencies or other treatment problems that may admit pathogens to the distribution system.

The method for analyzing turbidity is well established (EPA Method 180.1 or Standard Method 2130). Turbidity can be measured using on-line turbidimeters, portable turbidimeters, or bench top turbidimeters that meet EPA-approved methods.

Indicator of Breaches of Distribution System Integrity

Turbidity can be used as an indicator for identifying contamination entry, hydraulic problems or finished water reservoir rehabilitation frequencies in the distribution system. Sudden increases in turbidity can indicate main breaks, backflow, fire fighting or hydrant opening, flushing, scheduled maintenance or repairs, valve failures, and treatment failures in the distribution system (Kirmeyer et al., 2002b). Particles in treated drinking water may also be introduced during new construction.

Microorganisms can adhere to particles that protect them from disinfection, provide a source of nutrients, and facilitate their movement within the distribution system (Gauthier et al. 1999a; Morin et al. 1999). Furthermore, an increase in turbidity in the distribution system will exert a greater chlorine demand which could lead to inadequate disinfection of the distributed water (Kirmeyer et al., 2002b). Thus turbidity can be an indicator that conditions permit potential microbiological growth in the distribution system.

Increased turbidity near a finished water reservoir may be an indication of a water quality problem associated with the reservoir. Increased turbidity may be due to contamination in the storage tank, water age or mixing issues or tank material degradation (Kirmeyer et al., 2002b).

Advantages

The method for analyzing turbidity is well established (such as EPA Method 180.1 or Standard Method 2130). Turbidity testing is inexpensive if the system already owns a turbidimeter and analytical results can be obtained quickly. Water system operators can perform testing on-site. Systems required to continuously monitor for turbidity at the treatment facility will have a baseline when comparing the turbidity entering the distribution system to the turbidity within the distribution system.

Disadvantages

Turbidity is not an indicator for specific microbiological or chemical contaminants.

6.3 Other Indicators

6.3.1 Temperature

Background

Temperature is a very important parameter for many physical and chemical water treatment applications (AwwaRF, 2002). Changes in temperature are also important to predicting distribution system integrity breaches including mains breaks, corrosion, nitrification and changes in hydraulic conditions (NRC, 2006). Temperature difference between storage tanks and entry to the distribution system can suggest stratification in storage tanks and hence degradation of water quality that could lead to microbial regrowth in the distributions system (Mahmood et. al. , 2005). Many systems conduct online temperature monitoring both at entry points and within the distribution system

Indicator of Breaches of Distribution System Integrity

An increase in water temperature will also increase the rate of decay for chlorine (Zhou et al., 2003). A sudden change in water temperature could indicate a problem with distribution system integrity as water of a different temperature enters the system from a storage tank, backflow or intrusion.

Warmer temperatures are associated with increased growth rates of bacteria (Besner et al., 2002). Increases in summer occurrences of total coliform-positive samples have been reported (Colbourne et al., 1991; Olstadt et al., 1998). Coliform-positive samples occur more frequently when the distribution system water temperature is above 15° C (Volk and Joret, 1994; Volk and LeChevallier, 2000; Besner et al., 2001).

Warmer temperature is associated with an increase in corrosion potential (Besner et al., 2002). Water temperature can be used as an indicator to determine the corrosivity of water in the distribution system. For example nitrification, which can lead to corrosive water conditions, most commonly occurs at temperatures greater than 15°C (Kirmeyer et al., 2002b). Conversely, calcium carbonate has a higher tendency to precipitate and form a protective layer at higher temperatures, minimizing the effects of corrosion (AWWA, 2000).

Temperature can indicate potential leaching of vinyl chloride from PVC pipe. Fluornoy et al. (1999) conducted a survey of water systems using PVC pipe in their distribution systems. The study identified high temperatures (i.e., $\geq$ 50 °F) as promoting vinyl chloride leaching.

Advantages

Analyzing for temperature is simple and inexpensive since many water-quality field instruments have a means of measuring temperature that would not require separate instrumentation. Water system operators can measure water temperature on-site and the results are immediate.

Disadvantages

A change in temperature is not an indicator for specific types of contaminants.

6.3.2 Pressure

Background

Pathways by which contaminants can enter the distribution system during a pressure reduction event include cross connections, leaks, water main break and repair sites, and short-term pressure transients (Kirmeyer et al., 2001; EPA, 2002; Karim et al., 2003; WHO, 2004).

Pressure monitoring in all parts of the distribution system can identify changes in pressure that may leave a system vulnerable to contaminant entry into the distribution system (LeChevallier et al., 2002). Pathogens or chemicals in close proximity to pipes experiencing low or negative pressures are potential contamination sources even though they are external to the distribution system. Record keeping about events that contribute to pressure changes may aid systems in recognizing such events before they occur.

Gullick et al. (2004) used high-speed electronic monitoring devices to determine the frequency and location of low and negative pressures in representative distribution systems under normal operating conditions and during specific operational events.

Hydraulic modeling and transient surge modeling can be used to evaluate pressure changes and transient pressure waves associated with rapid changes in fluid velocity (Walski et al., 2001; Wood et al., 2005). Walski et al. (2006) defined the orifice/soil number as an indicator of head loss caused by orifice losses relative to porous media losses.

Indicator of Breaches of Distribution System Integrity

Friedman et al. (2004c.) conducted field studies, laboratory studies, and hydraulic modeling to verify and quantify the occurrence of low and negative pressure transients in distribution systems and the potential intrusion of contaminants external to the pipe caused by pressure transients. These pressure events are caused by sudden changes in water velocity due to loss of power, sudden valve closure or opening, a transmission line break, fire flow, or an uncontrolled change in on/off pump status. A pressure surge is created by these conditions, causing very high pressure followed by low and negative pressure. When the pressure surrounding the water main exceeds the internal pressure in the pipe, water external to the main may flow in through leakage points, submerged air valves, cross connections, faulty seals, or joints.

Indicator of Distribution System Contamination

Pressure measurement is a useful operational monitoring parameter that can be used as an indicator of possible contamination in piped distribution systems (WHO, 2004). Fecal contamination may occur in large buildings through cross-connections and backflow and from buried/immersed tanks and pipes, especially if not maintained with positive internal water pressure (WHO, 2004). The principal hazards that may accrue in the drinking-water systems of large buildings are ingress of microbial contamination (which may affect only the building or also the wider supply), proliferation and dispersal of bacteria growing on water contact surfaces (especially *Legionella*) and addition of chemical substances from piping, jointing and plumbing materials (WHO, 2004).

Boyd et al. (2004a; 2004b) assembled a pilot-scale test rig to simulate intrusion behavior associated with hydraulic transients and quantified intrusion volumes by two methods, chemical tracer and volumetric methods, and compared results to theoretical estimates of intrusion.

Indicator of Public Health Outcome

The public health significance of intrusion from a pressure transient depends on the number and effective size of orifices (leaks), the type and amount of contaminants external to the distribution system, the frequency, duration, and magnitude of the pressure transient event, and the population exposed (LeChevallier et al., 2002b). Continual monitoring for reduced pressure can give immediate warning of a potential backflow incident (EPA, 2002).

Outbreaks of fluoride poisoning were reportedly caused by backsiphonage at water treatment plants in Mississippi and Hawaii (Craun and Calderon, 2001). In Tennessee, high concentrations of *Giardia* found in samples collected at a correction facility attributed to low water pressure for 3 days and a likely cross-connection with the wastewater pump station (Craun and Calderon, 2001). In 1990, an outbreak of illnesses in Missouri was associated with municipal drinking water and attributed to sewage overflow in an area where meters were replaced and a water main break occurred (Craun and Calderon, 2001). The risks may be elevated seasonally as soil moisture conditions increase the likelihood of a pressure gradient developing from the soil to the pipe (WHO, 2004).

Sadiq et al. (2006) proposed the application of evidential reasoning to assess risk of contaminant intrusion in a given pipe. Data generated through routine water quality monitoring in distribution networks representing intrusion pathways, driving forces, and contamination sources can be combined with evidential reasoning to establish risk-contours of contaminant intrusion and help identify sensitive locations in water distribution networks, thus helping prioritize control strategies.

Advantages

An advantage of using pressure as an indicator of distribution system integrity is that data from pressure gages throughout the distribution system can be tied into a

SCADA system to provide water system operators with real-time data from the distribution system (Kirmeyer et al., 2002b). This allows rapid detection of potential problems in the distribution system with minimal need for operator labor. Continual monitoring for reduced pressure may identify the area where a pressure drop may have originated, and thus help isolate areas affected by backflow (EPA, 2002). Pressure monitoring devices are routinely used by utility personnel. High-speed devices are also commercially available (AWWARF, 2002).

Disadvantages

LeChevallier et al. (2002) described negative pressure events that were brief, lasting for only seconds or minutes. If pressure monitoring is to be used as an indicator of distribution system integrity, water pressure would need to be measured very frequently, if not continuously, in order to catch these brief and intermittent negative pressure events. High-speed pressure data loggers may be more sensitive than conventional pressure data loggers, and may be more useful for detecting low-pressure events. However, many would need to be used to monitor the entire distribution system and they are expensive.

A drop in operating pressure can only indicate that a backflow event may have already occurred; it cannot stop an event in progress or prevent an incident, unless the root cause is corrected (EPA, 2002).

Predictive tools using evidential reasoning (Sadiq et al., 2006) are early in development and not readily available.

6.3.3 Sanitary Survey Results

Background

Sanitary surveys are currently used to help identify deficiencies within the distribution system. As stated in the December 1995 EPA/State Joint Guidance on Sanitary Surveys (ASDWA/USEPA, 1995), the primary purpose of a sanitary survey is "to evaluate and document the capabilities of the water system's sources, distribution network, operation and maintenance, and overall management to continually provide safe drinking water and to identify any deficiencies that may adversely impact a public water system's ability to provide a safe, reliable water supply."

The TCR (40 CFR 141.21(d)) requires that systems taking fewer than 5 samples per month have a sanitary survey performed by the State every 5 years (10 years for some systems using protected and disinfected ground water sources). The frequency of sanitary surveys of systems using surface water or GWUDI as a source was modified by the IESWTR (40 CFR 142.16) to be no less than every 3 years for all sizes of community systems, and no less than every 5 years for non-community systems.

The IESWTR also requires that States have the authority to assure that public water systems using surface water or GWUDI sources respond in writing to significant deficiencies outlined in sanitary survey reports no later than 45 days after the system receives the report. In their response, water systems must indicate how and on what schedule they will address significant deficiencies noted in the survey. The Ground

Water Rule (GWR) requires that states have similar authority for sanitary surveys of groundwater systems.

The IESWTR and the GWR (USEPA, 2000) both identify the distribution system as one of the eight essential elements that must be addressed during the sanitary survey.

- Source (Protection, Physical Components and Condition)
- Treatment
- Distribution System (emphasis added)
- Finished Water Storage
- Pumps/Pump Facilities and Controls
- Monitoring/Reporting/Data Verification
- Water System Management/Operations
- Operator Compliance with State Requirements

In its *Guidance Manual for Conducting Sanitary Surveys of Public Water Systems; Surface Water and Ground Water Under the Direct Influence (GWUDI) of Surface Water* (USEPA, 1999b), EPA provides more specific objectives for addressing a system's distribution system during the sanitary survey. The three principal objectives of the distribution system element of the sanitary survey are the following:

- To determine the potential for degradation of the water quality in the distribution system
- To determine the reliability, quality, and vulnerability of the distribution system
- To ensure that the sampling and monitoring plan(s) for the system conform with requirements and adequately assess the quality of water in the distribution system

Sanitary surveys have preventive value in identifying actual or potential deficiencies within systems. As with issues of system integrity, deficiencies noted in a sanitary survey may be an indicator of present or possible future contamination in the distribution system. A survey on best management practices found that, while there was no relationship between conducting sanitary surveys and occurrence of total coliform positives, systems that corrected problems identified during sanitary surveys had fewer total coliform detections (USEPA, 1997).

Indicator of Breaches of Distribution System Integrity

The second objective listed immediately above essentially describes an assessment of the distribution system integrity. Sanitary surveys offer the opportunity to inspect above-ground facilities and to identify (to the extent practicable) line and valve locations, pipe sizes and materials, hydrant locations, locations of dead end mains, pressure zone boundaries, and locations of storage tanks and booster pump stations.

After assessing the physical condition of the system, the inspector may then be able to predict whether the system infrastructure could impact water quality and quantity. During the sanitary survey, inspectors typically also ask questions such as the following related to operation and maintenance of buried infrastructure (USEPA, 1999b):

- Are distribution system maintenance and repair records kept?
- How frequent are main breaks and where do they occur?
- Is a leak detection program in place?
- Are the source and service connection flows metered?
- Is a regular, systematic flushing program in place?
- Are distribution system installations, repairs and maintenance routinely disinfected?
- Is a cross-connection control program in place?

The answers to these questions, in conjunction with a knowledge of the system construction, may indicate integrity and potential contaminant pathway issues and whether there is potential for a problem in the distribution system.

As with issues of system integrity, deficiencies noted in a sanitary survey may be an indicator of present or possible future fecal contamination in the distribution system. For example, noted deficiencies, such as loose vents and overflows or an unsealed hatch could lead to fecal contamination of a water system if birds gained access to treated drinking water through the unprotected openings (Clark et al., 1994).

Indicator of Distribution System Contamination

During the sanitary survey, inspectors are also encouraged (USEPA, 1999b) to collect a total coliform surveillance sample. Thus, the combination of a positive total coliform test and noted deficiency which could lead to fecal contamination may provide an indication of the potential for fecal contamination.

Indicator of Public Health Outcome

Similar to that mentioned above, noting an unprotected opening during a survey may serve as an indicator that there is a high potential for a waterborne disease outbreak to have occurred prior to the survey and up to the point when the deficiency is fixed.

Advantages

As discussed above, sanitary surveys are already a required element of a state primacy program. State primacy agencies are therefore familiar with sanitary survey requirements and have existing programs in place.

Disadvantages

Since most of the distribution system components are located underground, they cannot be directly inspected on a routine basis. Therefore, the review tools used to evaluate the integrity of the distribution system during sanitary surveys include the system's design standards, installation procedures, and operation and maintenance practices. A comparison of system information to current federal, state, and industry standards and practices may then be made to assess the buried infrastructure components.

The exteriors of ground-level finished water storage tanks can typically be inspected during the sanitary survey, but the condition of tank interiors may be difficult to assess since tanks are normally filled with water and in use during the survey. Elevated tanks pose more significant challenges because of safety issues involved with tank access. Therefore, potential problems such as accumulated sediments, biological growth on the interior tank walls, or corrosion and peeling paint may not be clearly identified during the sanitary survey. As with the rest of the distribution system, inspectors may have to rely on information about the system's operational practices to assess the likely condition of the interior of the storage tank. These limitations somewhat complicate the use of sanitary surveys as an indicator for distribution system integrity.

While some states may require more frequent surveys, many adhere to the federal schedule. Water quality samples taken and deficiencies noted during a survey therefore provide a snapshot of conditions at points in time that may be separated by 3 to 5 year intervals, or perhaps even longer.

6.3.4 Water Loss

Background

All water systems have some degree of water loss. Water loss can be determined by comparing records of the amount of water pumped or flowing from the source(s) to the amount recorded on metered connections. However, accounting problems and meter inaccuracies may produce some error in water loss calculations. Water loss may also be estimated in unmetered systems by observing the drop in water level in a gravity storage tank during periods of normally low-water usage by consumers (e.g., late at night). Water loss occurs through leaks, main breaks, fire hydrant use, and unauthorized connections. A leaking main indicates a physical opening within the pipe that can create a pathway for contaminant entry.

The presence of leaking sewer lines in the vicinity of leaking water main breaks or repairs provides an opportunity for introduction of pathogens into drinking water systems. A waterborne disease outbreak in Cabool, Missouri, resulted from a main break with subsequent sewage contamination (Geldreich, 1992).

Indicator of Breaches of Distribution System Integrity

Systems with high leakage rates may also be more susceptible to main breaks, as well as intrusions when low pressures occur.

Indicator of Distribution System Contamination

Distribution system locations with shared characteristics of high leakage rates and being susceptible to low or negative pressures have the greatest potential for intrusion. Based on the findings of Friedman et al. (2004), systems can track low or negative pressures at those locations and infer that these low pressure readings may be effective indicators of increased likelihood of contamination.

Advantages

An advantage of monitoring water loss as an indicator of distribution system integrity is that many water systems already have meters at all service connections; so much of the needed equipment is already in place. Monitoring of losses may also lead to revenue savings where the causes of the losses are corrected.

Disadvantages

A disadvantage of using water loss monitoring as an indicator of distribution system integrity is that detection of water loss may not indicate where leaks are occurring. In order to narrow down where leaks are occurring, it may be necessary to monitor water loss in smaller zones within the distribution system, rather than solely at metered connections (AWWA, 2000). Leak detection equipment is also available.

7 Summary of Indicators by Distribution System Problem

This section summarizes each of the types of distribution system problems and the indicators that may be applicable toward identification of that problem.

Exhibit 3 Microbial Indicators

Indicator	Type of Distribution System Problem				
	Breaches of Distribution System Integrity		Contamination		Public Health Outcome
	External Pathways	**Internal Pathways**	**Fecal**	**Toxic or Carcinogenic**	**Waterborne or Endemic Disease**
Total Coliforms	X	X	*		X[1]
E. coli	X		X		X[2]
Thermotolerant (Fecal) Coliforms	X	X	X		
Heterotrophic Bacteria		X			
Total Bacterial Counts and Total Viable Bacterial Counts	X	X			
Pseudomonas and *Aeromonas*	X	X			
Enterococci and Fecal Streptococci	X		X		X
Somatic Coliphage			X		
Male-Specific Coliphage	X		X		X
Clostridium perfringens	X		X		
Bacteroides phage			X		

Notes:

* total coliforms may be a broad screen for the potential for fecal contamination since some fecal bacterial pathogens may be present when total coliforms are present.

[1] = potentially indicative of bacterial pathogens, but not viruses and protozoa (Nwachuku et al. 2002)

[2] = not all are pathogenic

Exhibit 4 Chemical Indicators

	Indicator of Type of Distribution System Problem				
	Pathways that breach distribution system integrity.		Contamination		Public Health Outcome
	External Pathways	Internal Pathways	Fecal	Toxic or Carcinogenic	Waterborne or Endemic Disease
Residual Disinfectant	X	X			X
pH	X	X			
Alkalinity	X	X			
Calcium		X			
Conductivity	X	X			
Fecal Sterols			X		
Caffeine and Pharmaceuticals			X		
AOC and BDOC		X			
ATP		X			
Endotoxin	X	X			
Iron	X	X			
Ammonia/Nitrate/ Nitrite/Nitrogen		X	X		
Aluminum		X			
Chloride	X		X		
Microbially Available Phosphorus		X			

Exhibit 5 Other Indicators

Indicator	Indicator of Type of Distribution System Problem				
	Pathways that breach distribution system integrity.		Contamination		Public Health Outcome
	External Pathways	Internal Pathways	Fecal	Toxic or Carcinogenic	Waterborne or Endemic Disease
Sanitary Survey	X		X		X
Turbidity	X				
Water Loss	X	X	X	X	
Temperature	X	X			
Pressure	X		X	X	X

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9 Appendices

9.1 Summary Table of Advantages and Disadvantages for Each Indicator

Indicator	Distribution System Applicability	Advantages	Disadvantages[1]
Microbial			
Total Coliforms	External Pathways, Internal Pathways Waterborne or Endemic Disease (weak)	• Densities are much greater than the density of fecal indicators • Useful in assessing treatment effectiveness and breaches in the distribution system. • Detection methods are simple and inexpensive, and laboratories are familiar with these methods. • Can be used as rough screen for fecal contamination.	• Determination of whether TCs are of fecal or environmental origin is difficult. • More sensitive to disinfection than some pathogens. • High levels of heterotrophic bacteria can interfere with total coliform analysis. • Do not provide good indication of specific contamination pathways. • Do not provide good indication of vulnerability to waterborne outbreaks unless possibly in conjunction with another indicator or with monitoring beyond TCR requirements.

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[1] All indicators have a common disadvantage in that they must be monitored frequently in many locations to be able to identify distribution system contamination events

Indicator	Distribution System Applicability	Advantages	Disadvantages[1]
E. coli	External Pathways, Fecal Contamination, Waterborne or Endemic Disease	• Analytical methods are simple, reliable, inexpensive, and produce results within 24 to 48 hours. • *E. coli* is closely associated with recent fecal contamination. • Presence indicates a major deficiency in the distribution system due to extreme sensitivity to disinfection.	• Typically lower in density than total coliforms in water. • *E. coli* may die out more quickly than some waterborne pathogens due to succumbing to environmental factors or to inactivation by disinfectants. • Sensitive to *Pseudomonas spp.*, which may affect ability to detect *E. coli*.
Thermotolerant (Fecal) Coliforms	External Pathways, Internal Pathways, Fecal Contamination Waterborne or Endemic Disease (weak)	• Analytical methods are simple, reliable, inexpensive, and produce results within 24 to 48 hours. • Easier to detect than *E. coli* due to typically being present in higher densities. • More specific indicator of fecal contamination than total coliforms. • Many thermotolerant coliforms are associated with recent fecal contamination.	• Analytical methods for thermotolerant coliforms can detect some environmental strains, capturing a larger group than the target organisms. • May be difficult to determine source of contamination. • See disadvantages for *E. coli*.
Total Heterotrophic Bacteria	External Pathways (weak), Internal Pathways (weak)	• Analytical methods are simple, reliable, inexpensive, and produce results within 48 hours. • Effective indicator of biological growth.	• High HPC measurements can indicate a range of issues and cannot identify if the problem is of fecal origin. • Standard HPC method is insensitive to many waterborne bacteria. • Measurements can be unreliable due to difference in methods, sample location, and season.

Indicator	Distribution System Applicability	Advantages	Disadvantages[1]
Total Bacterial Counts	External Pathways, Internal Pathways	• Total counts provide basic information on numbers of bacteria in water. • Viable counts may warn of significant problems. • The analytical methods for viable counts are relatively simple, inexpensive, and well-established. Total bacterial counts capture bacteria that will not grow on artificial media.	• Total counts can not distinguish viable and nonviable cells. • Total counts are tedious and time-consuming.
Pseudomonas and *Aeromonas*	External Pathways, Internal Pathways	• May indicate inadequate chlorine residual or the presence of biofilm growth.	• *Pseudomonas* and *Aeromonas* capture a smaller variety of biofilm bacteria compared to other potential indicators. • The presence of pseudomonads may interfere with the recovery of other organisms on certain growth media • *Pseudomonas* and *Aeromonas do not provide an index of fecal contamination.*
Enterococci and Fecal Streptococci	External Pathways, Fecal Contamination, Waterborne or Endemic Disease	• Standardized analytical methods are available, relatively easy to use, and provide rapid results. • Are generally absent from pure, unpolluted waters (except in tropical climates). • EPA recommends using enterococci in conjunction with *E. coli* as a good indicator of fecal contamination.	• Not as good a fecal indicator when pathogenic protozoa are present which are more resistant to environmental stress and disinfection than enterococci and fecal streptococci.

Indicator	Distribution System Applicability	Advantages	Disadvantages[1]
Somatic Coliphage	Fecal Contamination (weak)	• Standardized methods are available.	• No direct correlation in numbers of phages and viruses in human feces. • Somatic coliphages can be found in conditions without presence of fecal contamination or a health risk. • Enteric viruses have been detected in water environments in the absence of coliphages. • Analytical method is more complicated and expensive than those for traditional bacterial indicators.
Male-Specific Coliphage	External Pathway, Fecal Contamination	• Somewhat resistant to disinfection. • Standardized methods are available for use in drinking water. • Narrow host range in comparison to somatic coliphage. • Correlate better with presence of pathogens in human feces than somatic coliphage.	• Difficulty in producing reproducible results. • There is no direct correlation in numbers of phages and viruses in human feces. • Methods are not accessible due to complexity and time. • May not be specific to *E. coli.* • Numbers may be sensitive to temperature conditions.
Clostridium perfringens	External Pathways, Fecal Contamination	• Definitive fecal indicator. • Standardized methods are available for rapid and reliable recovery of the organism from water. • Correlates statistically with concentrations of enteric viruses and presence of *Giardia cysts* in drinking water.	• Due to persistence of spores for long periods, may result in false positives. • The analytical method is more complex than the coliform methods.

Indicator	Distribution System Applicability	Advantages	Disadvantages[1]
Bacteroides fragilis phages	Fecal contamination	• Does not grow in the environment. • May indicate very recent human fecal contamination.	• Complex analytical methods are required. • Bacteroides is an obligate anaerobe that quickly dies in the environment. • Absence of this phage does not provide evidence of the absence of fecal contamination.

Indicator	Distribution System Applicability	Advantages	Disadvantages
Chemical			
Residual Disinfectant	External Pathways, Internal Pathways, Waterborne or Endemic Disease	• EPA-approved analytical methods exist. • Analytical methods are cheap and results are immediate. • Reductions in residual disinfectant may indicate contamination from many different types of sources.	• Frequency of monitoring may not be often enough to capture short-term events. • Historical records are necessary for comparison. • No documented cases could be found where a reduction alerted operators or officials to a waterborne disease outbreak. • Does not identify a single contaminant pathway.

Indicator	Distribution System Applicability	Advantages	Disadvantages
pH	External Pathways, Internal Pathways	• Many systems already monitor for pH, have equipment and are familiar with pH measurement.	• A change in pH does not identify a single contaminant pathway. • pH changes may be minimized by highly buffered water. • Equipment used for measurement must be routinely maintained and calibrated. • Equipment may be expensive to purchase, depending upon site-specific monitoring requirements.
Alkalinity	External Pathways, Internal Pathways	• Method is well established and inexpensive. • Results are obtained quickly. • Testing can be performed on-site.	• Alkalinity is not an indicator of a specific problem. • Current monitoring is typically limited in scope and frequency due to current regulations. • Baseline conditions would need to be established before this could provide indication of water quality changes.
Calcium	Internal Pathways	• Method is well established and fairly inexpensive. • Analytical results can be obtained quickly.	• Calcium is not an indicator of a specific contaminant. Would need to be used in conjunction with other indicators or information.
Conductivity	External Pathways, Internal Pathways	• Method is well established and fairly inexpensive. • Measurement can be continuous. • If the system has the necessary instrumentation, results are immediate.	• Conductivity is not an indicator of a specific contaminant. Would need to be used in conjunction with other indicators or information.

Indicator	Distribution System Applicability	Advantages	Disadvantages
Fecal Sterols	Fecal Contamination	• Fecal sterols may allow differentiation between human sewage pollution and fecal contamination from animals.	• The analytical method is expensive and complex. • Many drinking water treatment facilities do not have this equipment. • Do not indicate non-fecal contamination. • May be present in source water and it is questionable how much is removed during treatment.
Caffeine and Pharmaceuticals	Fecal Contamination	• The caffeine concentration in waste waters is typically much greater than in drinking water. • The presence of pharmaceuticals is a clear indicator of human-caused pollution.	• The analytical method is expensive and complex. • Many drinking water treatment facilities do not have this equipment. • Caffeine can break down in the environment. • Presence of pharmaceuticals is unpredictable. • Because some plants produce caffeine, it is not associated solely with fecal contamination. • May be present in source water and it is questionable how much is removed during treatment.
AOC and BDOC	Internal Pathways	• Several studies have shown that limiting AOC concentrations can control the growth of biofilms in the distribution system.	• The analytical method can be expensive and 2 to 3 days up to 4 weeks are required to obtain results. • Although limiting AOC concentrations has been shown to control biofilms, measuring AOC alone may not be an accurate predictor of microbial growth.

Indicator	Distribution System Applicability	Advantages	Disadvantages
ATP	Internal Pathways	- General indicator for biofilms and microbial growth.	- The bioassay method for measuring ATP is a complex method. - There is no EPA-approved method for ATP. - Rapid, easy methods have been developed for use in the food industry, but their applicability to treated drinking water is not known. - There is limited application for ATP testing at temperatures less than 10 ^{o}C or for stressed cells. - Interpretation of data may be difficult.
Endotoxin	External Pathways, Internal Pathways	- A highly sensitive standard method is available. - Test kits are available for use on-site.	- There is poor correlation between endotoxin results and HPCs. - Limited specificity as an indicator.
Iron	External Pathways, Internal Pathways	- High concentrations of iron clearly indicate corrosion and increased concentrations could indicate sloughing. - The analytical method is fairly inexpensive and may detect additional metals.	- It is difficult to relate measurement of iron to location of actual problem due to migration.
Ammonia/Nitrate/ Nitrite/Nitrogen	Internal Pathways, Fecal Contamination	- The analytical method is relatively easy.	- Monitoring may become expensive if continuous monitoring is employed.
Aluminum	Internal Pathways	- Sampling and analysis are relatively straightforward and inexpensive. - Sampling in pipe sections with cement-mortar lining may easily detect aluminum leaching.	- Detection of elevated aluminum does not identify the corrosive conditions. Further investigation may be necessary. - Alum floc may accumulate in distribution system.

Indicator	Distribution System Applicability	Advantages	Disadvantages
Chloride	External Pathways, Fecal Contamination	- The analytical method is relatively simple and inexpensive.	- There are multiple potential sources and the source of contamination may not be clear.
Microbiological Available Phosphorus	Internal Pathways	- Insufficient information.	- The analytical method takes 4 to 8 days. - The critical concentrations and effects are not sufficiently documented to determine a level to which MAP should be limited.
Turbidity	External Pathways	- The analytical method is well-established and relatively inexpensive. - Many systems already monitor turbidity entering the distribution system, which can be used to establish a baseline.	- Turbidity is not an indicator of specific contaminant.

Indicator	Distribution System Applicability	Advantages	Disadvantages
Other			
Temperature	External Pathways, Internal Pathways	- Method is well established, simple, and inexpensive. - Testing can be performed on-site and results are immediate.	- Temperature change is not an indicator of a specific contaminant.

Pressure	External Pathways, Fecal Contamination,	• Continual monitoring may identify the area where a pressure drop originated and isolate areas affected by a backflow event.	• Only provides information on an event that may have already occurred. • Pressure would need to be measured very frequently in order to catch brief and intermittent negative pressure events. • Predictive tools are in early development and not readily useable.
Sanitary Survey	External Pathways, Fecal Contamination, Water-borne or Endemic Disease	• States and systems are familiar with sanitary survey requirements.	• Buried distribution system components cannot be directly inspected. • Interiors of storage tanks that are in service cannot be easily accessed. • Sanitary survey frequency is 3-5 years.
O&M Practices	External Pathways, Internal Pathways, Fecal Contamination, Toxic or Carcinogenic Compounds	• Many systems already have meters at all service connections, so equipment necessary for monitoring for water loss is already in place.	• Customer complaints are voluntary. • Water loss monitoring may not indicate specifically where leaks are occurring.