According to the Total Coliform Rule, coliform bacteria constitute the main indicator used to detect microbial contamination in distribution systems. A major goal for water utilities is to prevent and control coliform occurrences and noncompliance (with respect to regulations). However, the applied solutions are sometimes successful only to a limited extent because of the variety of factors that may give rise to these occurrences. It is therefore important to identify those factors—from the structure and operation of the distribution system to the quality of the distributed water itself—that can influence the occurrence of coliform bacteria in a distribution system. The use of the identified factors makes the modeling of coliform occurrences attractive, and a number of approaches for doing so have recently been proposed. This article provides a review that includes the mechanisms of how coliform bacteria are introduced into treated and distributed drinking waters, the major factors controlling the survival and regrowth of coliforms once introduced into the system, and the modeling efforts carried out to explain or predict their occurrence.

BY MARIE-CLAUDE BESNER, VINCENT GAUTHIER, PIERRE SERVAIS, AND ANNE CAMPER

Explaining the occurrence of coliforms in distribution systems

The coliform group of bacteria is used worldwide as an indicator of the microbiological quality of drinking water (WHO, 1993). The group mainly consists of several genera of bacteria belonging to the *Enterobacteriaceae* family, mostly *Escherichia, Klebsiella, Enterobacter, Citrobacter,* and *Serratia*. The detection of coliforms in tap water is supposed to indicate to utilities and health authorities that a breach has occurred in treatment or in the distribution system, allowing microbial (fecal) contamination of water to occur and thereby rendering it inappropriate for drinking.

In practice, coliforms are found quite often in tap water. However, the magnitude of the health risk associated with their presence has been somewhat mitigated—a tolerance of 5% for water samples testing positive for nonfecal coliforms on a monthly basis is allowed in the United States (USEPA, 1989). This was done to take into account the fact that several of these microorganisms occur naturally in the aquatic environment, originating from soil and vegetation (Kreig, 1984) or industrial activities (Archibald, 2000). Because many coliforms are able to survive and regrow in a distribution system (LeChevallier, 1990), their presence does not necessarily indicate recent contamination. It is also worth mentioning that bottled water has been shown to present coliform occurrence rates that are similar to those in tap water samples (Warburton et al, 1998).

The validity of using coliforms as indicators of the microbiological quality of drinking water may be questioned because coliforms are sometimes detected when there is no evidence of contamination and they are sometimes not detected when pathogenic organisms are found in the water. Craun et al (1997) reported coliform detection during most (64%) of the waterborne illness outbreaks caused by bacteria, viruses, and

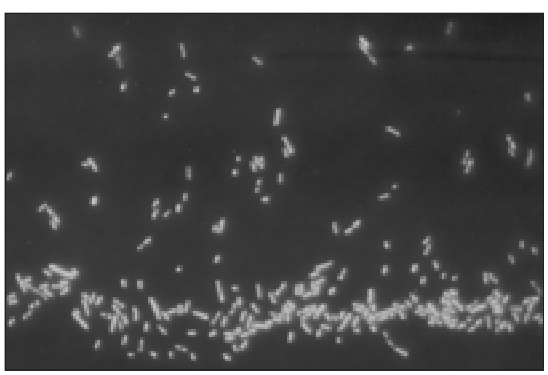
TABLE 1 Prioritization of pathogen entry routes into distribution systems*

Entry Routes Priority	Ranking
Water treatment breakthrough; transitory contamination; cross-connection; water main repair or breakage	High
Uncovered storage facilities	Medium
New main installation; covered storage facilities; deliberate contamination	Low

*Modified from Kirmeyer et al, 1999

unidentified agents from 1983 to 1992 in the United States. However, coliforms were only detected in a few (35%) outbreaks caused by protozoa. Similar results have also been reported in the United Kingdom (Furtado et al, 1998). Other studies (Payment et al, 1997; Zmirou et al, 1995; Payment et al, 1991) suggest that there is a low but significant risk of gastrointestinal illness from the consumption of water meeting the current bacteriological regulations. To improve the link between fecal contamination and regulations, *Escherichia coli* has been proposed as a better indicator than total coliforms since simple analytical techniques have recently been made available (Edberg et al, 2000).

However, until the Total Coliform Rule (TCR) is revised, water utilities will continue to use total coliform bacteria to assess the microbiological quality of their drinking water to comply with US regulations (Pontius, 2000). Consequently, efforts should be continued to prevent and control total coliform occurrences and noncompliance (with respect to regulations) and their possible association with contamination of distribution system waters. It is thus important to identify the factors—from the structure and operation of the distribution system to the quality of the distributed water itself—that can influence the occurrence of coliform bacteria in the distribution system (Craun & Calderon, 1999). With this in mind, this article provides a review including the mechanisms of how coliform bacteria are introduced into treated and distributed drinking waters, the major factors controlling the survival and regrowth of coliforms once introduced into the system, and the modeling efforts made to explain or predict their occurrence.



Suspension of coliform bacteria (*Enterobacter cloacae*) is observed by epifluorescence microscopy after staining with DAPI.

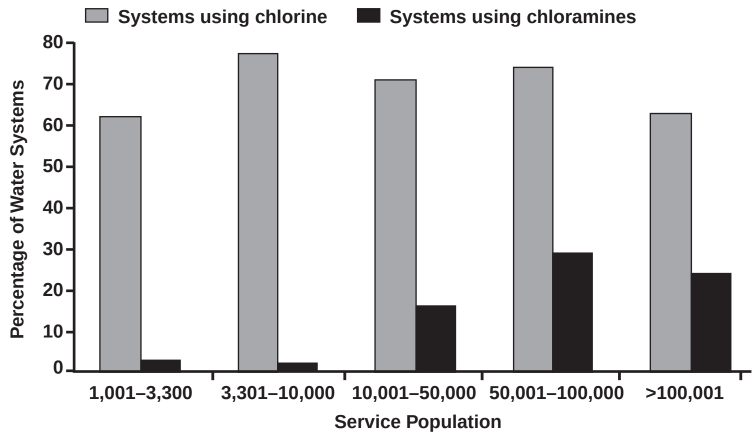
MECHANISMS OF COLIFORM INTRODUCTION

Two primary mechanisms are responsible for the introduction of coliform bacteria into a distribution system. Coliforms may break through into treated water as a result of inadequate treatment or be introduced as a result of intrusion into the distribution system downstream of the treatment plant (Craun & Calderon, 2001). These two pathways are usually very difficult to distinguish, because only a very small fraction of the total amount of treated water is tested for coliforms, and intrusion into the distribution system may be very localized in time and space. In some cases, epidemiological studies have helped in identifying that leakage and cross-connections, associated with low pressures, were responsible for tap water contamination (Semenza et al, 1998). In other cases, the detailed identification of the microorganisms involved has helped in identifying their origin (O'Neill & Parry, 1997; Edberg et al, 1994). But, in most cases, the origin of coliforms found in distribution systems remains unclear. Recently, one study (Kirmeyer et al, 1999) proposed a prioritization of entry routes into the distribution system (Table 1). The study concluded that as in treatment breakthrough, intrusion from transitory low-pressure events, cross-connections, and pipe repairs constituted a high risk of contamination.

Treatment breakthrough. Coliform presence in treated water is seldom reported, which is logical because the treatment is usually designed to inactivate or at least remove bacterial contamination, and its efficiency is evaluated using coliform-indicator bacteria. Nevertheless, this absence of coliforms in treated water may only be apparent because of the very small fraction of treatment effluents monitored, making the detection of a time-limited breakthrough illusory (the fraction of the volume sampled for coliform analysis usually ranges from $1/10^6$ to $1/10^9$). Low percentages of treated water samples testing positive for coliform bacteria (<0.2%) have been reported in treated water from two Canadian treatment plants, one of which uses granular activated carbon (GAC) filtration (Morissette et al, 1999). It is not known whether these coliforms pass through the filters or grow in them. Colonization of GAC filters with coliforms was demonstrated by Camper et al (1985) and was also suspected by Montiel and Welté (1999), who systematically recovered thermotolerant coliforms from the effluent of GAC filters during periods of high summer temperature (> 80% of the samples tested positive).

Coliforms may also remain undetected as a result of the cultivation techniques used for coliform detection—some or all of the coliforms may be injured (and not killed) by disinfection and thus unable to grow on traditional agar media. Various modified cultivation techniques have been proposed to permit the enumeration of injured coliforms (McFeters, 1990; McFeters et al, 1986; LeChevallier & McFeters, 1985). Using modified cultivation techniques, McFeters et al (1986) found injured coliforms in the effluent of three US facilities, and Craddock and Castle (1997) detected injured coliforms in 10.4% of 173 treated water samples from four treatment plants in the United Kingdom, while routine bacteriological tests indicated that only 0.6% of the samples were coliform-positive. The injured coliforms were found in the effluent of the three tested plants treating surface water, while they were undetected in treated borehole water, and positive samples were mainly associated with backwashing of the sand filters.

FIGURE 1 US community surface water systems using monochloramine as a secondary disinfectant



Source: USEPA, 1997

Release of particulate matter in treated water may facilitate the introduction of coliforms into the distribution system and may play an important role in treatment breakthrough. Examination of the particles released from GAC filter beds (Camper et al, 1986) showed that up to 17% of the samples contained carbon particles colonized with coliform bacteria. It has, in fact, been shown that cellular aggregation and attachment of bacteria to particulate matter result in the protection of microorganisms from disinfection (Gauthier et al, 1999a; Morin et al, 1999; Stringfellow et al, 1993; Berman et al, 1988; Herson et al, 1987; Ridgway & Olson, 1982).

Coliforms may also be associated with other types of particles such as invertebrates. Although most of the invertebrates that enter a water treatment plant are usually trapped and removed, organisms such as nematodes, rotifers, and protozoa have been observed in treatment plant effluent by many authors (Gauthier et al, 1997; Schreiber et al, 1997; Van Lieverloo, 1997; Brazos & O'Connor, 1996).

The presence of these organisms in treatment plant effluent may contribute to the introduction of coliforms into the distribution system. Schoenen & Hoyer (2000) have related the detection of total coliform in the treated water of a German plant to the presence of the larvae of gnats on filters and enumerated as many as 2×10^7 nonfecal coliform colony-forming units (cfu)/gnat larva. Moreover, laboratory studies have shown that organisms such as protozoa (amoebae and ciliates), nematodes, and amphipods can ingest bacteria such as *Escherichia coli* or *Enterobacter cloacae* and protect them from disinfection (Ding et al, 1995; King et al, 1988; Levy et al, 1986).

Another study (Lupi et al, 1995) conducted analyses on the intestinal contents of nematodes isolated from treated surface water and detected the presence of *Enterobacteriaceae* of environmental origin (up to 13 cfu/nematode), the majority of which were *Serratia*. Particulate matter and invertebrates might thus protect some coliforms from treatment plant disinfection and transport them into the distribution system.

In most cases, the presence of coliforms in treated water results from inadequate treatment settings or performance with respect to raw water quality. High bacterial loads in the source water are often a result of rainfall (Geldreich, 1996) and have been associated with higher coliform occurrences in the distribution system (LeChevallier et al, 1996b; LeChevallier et al, 1991). Several hypotheses may explain such occurrences, including less-efficient treatment in such conditions and change in organic matter causing coliform regrowth downstream in the distribution system. The latter hypothesis is supported by the lag between rainfalls and distribution system coliform occurrences (LeChevallier et al, 1991).

Contamination of groundwater following heavy rains combined with inadequate chlorine disinfection resulted in the contamination of the Walkerton distribution system (Canada) with *E. coli* O157:H7. The resulting major outbreak affected 1,346 people and killed at least 6 people (Health-Canada, 2000). Contamination of groundwater also resulted in recent *E. coli* outbreaks at a New York fair (Yarze & Chase, 2000), in Ontario (Jackson et al, 1998), in Europe (Chalmers et al, 2000), and in viral outbreaks that were initially detected as a result of analysis for fecal coliform (Häfliger et al, 2000; Kukkula et al, 1997). The protection of groundwater catchment areas is crucial to avoid contamination. For example, one study (Raina et al,

TABLE 2 Factors related to increased coliform occurrence in the Seattle, Wash., distribution system*

Factors	Effect on Coliform Occurrences
Lack of adequate chlorine residual in distribution system pipes	Inadequate disinfection of the coliform bacteria
No filtration of the source water	May increase the passage of coliform from the water source into the system, allowing coliform attached to particulate matter to pass through the disinfection barrier
Presence of uncovered reservoirs	Allows water contamination (particularly from birds and animals); increases the water residence time in the system
Presence of numerous storage tanks	May result in long water residence time, so that particulate matter harboring coliforms tends to settle and accumulate in the tanks
Inadequate flushing program (dead ends only)	Protection of the coliforms in pipe biofilm
Corrosion-control program only initiated in 1982	Protection of coliforms in corrosion by-products, particularly in unlined cast-iron pipes

*From Oliver and Pimentel, 1998

1999) observed significant association between the presence of *E. coli* in domestic well water and gastrointestinal illness. In this case, the relationship depended on the distance of the well from the house's septic tank. In contrast, no recent outbreak has been associated with the failure of surface water treatment plants to inactivate coliform organisms.

Therefore, the potential exists for coliforms to penetrate into distribution systems. Coliforms may be present even if they are not detected as a result of insufficient sampling or difficulties in measuring them, either because of their disinfectant-induced injured state or because of their association with (bio)particles.

Intrusion. A high potential risk of introduction of coliform bacteria and enteric viruses into the distribution system exists when transient negative pressure occurs in pipelines (LeChevallier et al, 1999). The study conducted by these authors indicates that fecal indicators and culturable enteric viruses can be detected outside distribution pipelines. Consequently, in a case in which there are pipe leaks, there exists a potential portal of entry of microorganisms into the distribution system during negative pressure events originating from pump starting or stopping, transmission main breaks, rapid opening or closing of valves, loss of power, hydrant flushing, and other conditions, especially on elevated sites (Kirmeyer et al, 1999). Illustrating this path of intrusion, McMath & Casey (2000) measured subatmospheric pressures at one distribution system point downstream of the pumping station of a UK system during surges. They observed that this point (an air valve chamber) was flooded with dirty water during wet weather, thus explaining the high coliform failure rate in the corresponding distribution system area.

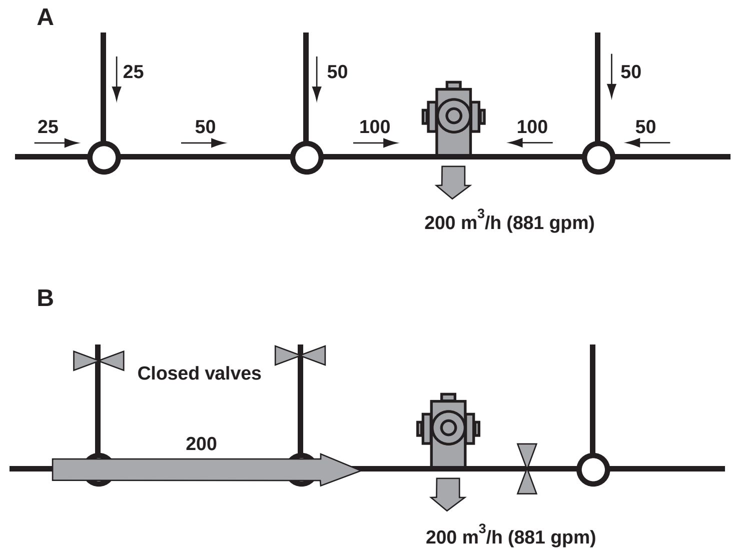
Contamination of the distribution system may also occur when a water main breaks or is repaired. Two major distribution line breaks were the suspected sources of contamination in the Cabool, Mo., outbreak of *E. coli* O157:H7, which caused 243 known cases of diarrhea and four deaths (Geldreich et al, 1992). Moreover, contamination may also occur if cleaning and disinfection procedures following repair are not adequately executed. LeChevallier (1999) noted that the flushing velocity of a repaired pipe is not always sufficient (often too low) to totally remove contamination. Pizzi (1996) also noted that a negligent worker with only a small amount of dog feces on the sole of his boot could contaminate many kilometres of pipes if disinfection following repair was inadequate. Contaminated sediment introduction during pipe repairs was also the main suspected cause of recurrent coliform occurrence in a dead-end area of a Canadian distribution system studied by Gauthier et al (1999b). Another study (Haas et al, 1999) reported that for 16% of the utilities surveyed, 1% of the first samples taken following new main disinfection showed a positive result for total coliform. These authors supported—and completed—the current AWWA standards for such disinfection procedures.

Cross-connections, defined as connections between a potable drinking water supply and a nonpotable, undesirable, or contaminated source, may also pose a threat to distribution system integrity (Herrick, 1997). Coliform bacteria and contaminated water may be introduced into distribution pipes from the backflow of water through the cross-connections because of a differential in pressure between the connected systems, especially during low-pressure events in the distribution system. Lahti & Hiisvirta (1995) reported two outbreaks in Finland caused by cross- connections involving sewage and seawater, both showing evidence of the presence of *E. coli.*

Numerous backflow incidents that have occurred throughout the United States are listed on the website of the American Backflow Prevention Association (1995), demonstrating that almost any kind of liquid can penetrate a distribution system through backflow. Garden hoses are among the most common causes of cross-connections (Herrick, 1997), and fire sprinkler systems may also be problematic (Dubay, 1997). Nevertheless, a detailed investigation of the water quality in 84 wet-pipe fire sprinkler systems (Duranceau et al, 1998) has shown that total coliforms were mostly absent from those systems and that the main risk of microbial contamination of the distribution system through backflow remains directly linked to the intrusion of sewage or raw water. Such an intrusion could eventually result in the colonization of the distribution system with coliforms, but this has not been confirmed experimentally—two separate studies (McMath et al, 1999; Sibille et al, 1997) were not able to recover fecal contamination indicators following the passage of a slug-dose of sewage in an experimental distribution system.

Uncovered finished water reservoirs located on distribution systems represent another potential source of fecal contamination of potable water supplies from birds and other animals. LeChevallier et al (1996b) have confirmed that the presence of open finished water reservoirs is one of the factors responsible for increasing the number of coliform occurrences. Water in closed storage tanks may also be contaminated if maintenance is inadequate. An outbreak of *Salmonella typhimurium* in Missouri probably resulted from bird contamination in a municipal water storage tank (Clark et al, 1996). The tank had an inappropriate roof vent and an uncovered hatch, which allowed free access to wild birds. Feathers were also discovered in the tank. For concrete tanks, contaminated water ingress through a tank's roof may also be detected by coliform presence in the water, indicating that remedial action (roof repair) needs to be taken (O'Neill & Parry, 1997).

FIGURE 2 Difference in flow repartition during conventional (A) and unidirectional (B) flushing



Identification of the source of entry. For many utilities, the origin of coliforms found in distribution systems remains unclear, and multiple solutions are applied to eliminate them (Kirmeyer et al, 2000). For example, the Washington, D.C., water supply system experienced a series of microbial violations under the TCR between September 1993 and July 1996 (Clark et al, 1999). The passage of coliform organisms into the distribution system resulting from treatment barrier breakthrough was evidenced by the measurement of total coliforms in treated water samples, but a sanitary survey of the storage facilities and of the distribution system also indicated numerous operational and maintenance deficiencies in the system, which could favor the intrusion of coliform bacteria into the distribution system from an external source (Clark et al, 1999).

The City of Seattle also experienced total coliform occurrences in 1993 and attributed them to a number of factors (Table 2). Short-term actions consisted of the adjustment of disinfectant residuals and the implementation of unidirectional flushing, which was very efficient in controlling coliform occurrences (Oliver & Pimentel, 1998; Oliver & Harbour, 1995). The number of positive samples for coliforms at the Metropolitan Water District of Southern California was reduced by improving sampling point protection and cleaning, thereby preventing airborne contamination (Gueco et al, 1999). In many other cases, coliform problems were apparently solved by increasing the disinfectant residual without clearly identifying the origin of the coliforms (Kirmeyer et al, 2000; Norton & LeChevallier, 1997; Holt et al, 1995).

FACTORS AFFECTING COLIFORM SURVIVAL AND GROWTH

Once coliform bacteria are introduced into a distribution system, they can be transported with the bulk flow of water, colonize, and grow in biofilms on pipe surfaces or in deposits. The ability of coliform bacteria to survive and even grow in drinking water biofilms has been demonstrated by many authors in pilot distribution system studies (Camper, 1996; Fass et al, 1996; Jones & Bradshaw, 1996; Camper, 1995; Standridge et al, 1995). Regrowth of coliforms was also evidenced in a full-scale distribution system (Edberg et al, 1994; LeChevallier et al, 1987). The issue of coliform regrowth in drinking water has previously been reviewed by LeChevallier (1990).

Water temperature. Water temperature affects all processes involved in microbiological water quality: microbial growth rate, disinfection efficiency, decay of disinfectant residual, corrosion rates, and distribution system hydraulics (increased water velocity from increased consumer demand) (LeChevallier, 1990). In most of the reported cases, more coliform occurrences have been noted in distribution systems during summer months when water temperatures are at their highest (Olstadt et al, 1998; Colbourne et al, 1991; Wierenga, 1985; Hudson et al, 1983). Many authors (Besner et al, 2001; Volk & LeChevallier, 2000; LeChevallier et al, 1996b; Volk & Joret, 1994; LeChevallier et al, 1991) have associated coliform growth with water temperatures higher than 15°C (59°F).

Unidirectional flushing may remove deposit-associated coliforms from distribution systems.

Type and concentration of disinfectant. Maintenance of a chlorine residual throughout the distribution system is usually recommended to minimize bacterial growth and coliform occurrence. However, some European utilities located in the Netherlands, Germany, Switzerland, and France are successfully producing and distributing hygienically safe and biologically stable drinking water without a disinfectant residual (Klein & Forster, 1999; Van der Kooij et al, 1999; Fokken et al, 1998; Lévi et al, 1992). The application of multiple treatment barriers, the production of biostable water, and the use of biostable materials for distribution infrastructures—as well as the application of protective measures to prevent recontamination in the distribution system—permit such a practice (Te Welscher et al, 1998; Van der Kooij et al, 1995). In North America, as well as in the United Kingdom, the use of disinfectants remains the favored approach to control microbiological water quality in the distribution system (Trussell, 1999).

Although chlorine is less efficient for the inactivation of biofilm bacteria than for bacteria present in bulk water (Parent et al, 1996; Servais et al, 1995; Mathieu et al, 1992; Paquin et al, 1992; Van der Wende & Characklis, 1990), relatively low chlorine concentrations have, in some cases, been successful in controlling the presence of coliform bacteria in a distribution system. Free chlorine thresholds varying from 0.05 to 0.5 mg/L in full-scale distribution systems have been quite useful in keeping the rate of occurrence of coliforms low (Besner et al, 2001; Volk & LeChevallier, 2000; Kiéné et al, 1999; LeChevallier et al, 1996b; Volk & Joret, 1994), especially when combined with a good biological stability of the treated water (Gatel et al, 2000). A pilot distribution system study (Parent et al, 1996) showed that as soon as chlorine could be detected in the system under study (0.1 mg/L), it inactivated the coliforms in the water phase. The only question at this time is whether the disinfectant really inactivates the coliforms or if they are still viable but just nondetectable by cultivation on selective media (injured coliforms). This uncertainty is undoubtedly promoting the development of alternative methods for detecting coliform bacteria in water samples.

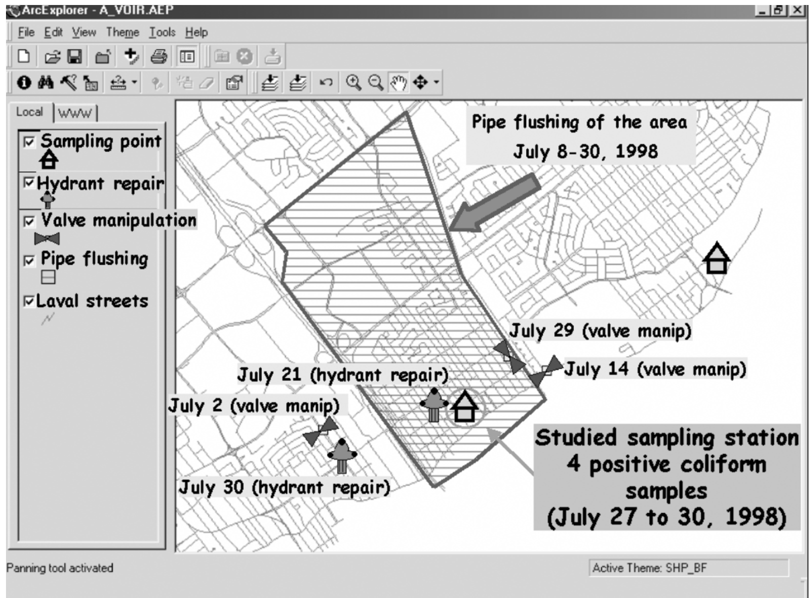
In contrast, many authors have reported that even high chlorine doses are ineffective in controlling coliform occurrence. Coliform-positive samples have been reported to occur in distribution systems with free chlorine residuals ranging from 0.6 to 4.0 mg/L (Schreppel & Geiss, 1996; Norton et al, 1995; LeChevallier et al, 1987; Ludwig et al, 1985; Wierenga, 1985; Martin et al, 1982). Even though increasing chlorine residuals has helped to control coliform occurrence in some cases (LeChevallier, 1990; Hudson et al, 1983), such chlorine increases may not always be an acceptable solution because of the formation of potentially carcinogenic disinfection by-products (DBPs) (Marret & King, 1995).

Because the use of chlorine has several drawbacks (taste, odor, halogenated compound formation) and does not totally guarantee a coliform-free drinking water, some utilities have looked at alternative disinfectants, such as chloramines, to control microbiological quality in the distribution system (Figure 1). Monochloramine is generally considered to be a less-effective disinfectant than free chlorine because higher concentrations are needed for a similar level of bacterial inactivation (Mathieu et al, 1992). However, because chloramine is a less-reactive disinfectant, it is more stable than free chlorine and persists longer in the distribution system. Its use is therefore beneficial in water networks where it is difficult to maintain a free chlorine residual because of corrosion or high water residence times (Song et al, 1998; Colbourne et al, 1991). However, many utilities first switched to monochloramine as a secondary disinfectant in order to comply with DBP regulations rather than to control total coliforms (Kreft et al, 1985; Mitcham et al, 1983).

The use of monochloramine also proved, in many cases, to be more effective than free chlorine in controlling coliform growth in bench-scale units (Momba et al, 1999; Camper et al, 1997) and in full-scale distribution systems (Norton & LeChevallier, 1997; LeChevallier et al, 1996b). The combination of monochloramine stability and its superior ability to penetrate biofilm has resulted in both greater efficiency with respect to attached organisms and better coliform control (LeChevallier et al, 1990). However, the use of monochloramine does not necessarily represent the perfect solution to coliform occurrence in the distribution system because it is less efficient than free chlorine in controlling a sudden pulse of contamination (Snead et al, 1980) and can lead to nitrification episodes (Wilczak et al, 1996).

Bacterial nutrients. In drinking water, the limiting nutrient for the growth of heterotrophic bacteria is usually the biodegradable fraction of dissolved organic carbon (DOC), even though the limitation of bacterial growth because of the availability of phosphorus has also been shown in some distribution systems (Miettinen et al, 1997; Sathasivan et al, 1997). This biodegradable fraction is usually expressed in terms of assimilable organic carbon (AOC) or biodegradable DOC (BDOC) concentrations, reflecting two types of analytical procedures (Huck, 1990). Studies have shown that AOC (LeChevallier et al, 1987) and BDOC (Servais et al, 1995; Servais et al, 1992) generally decrease with increased residence time of the water in the distribution system. It was hypothesized that such a decrease is caused by carbon utilization by bacteria and subsequent growth. Thus, bacterial regrowth may be limited by decreasing the AOC and BDOC content of the water leaving the plant.

FIGURE 3 Use of geographic information system–type visualization tools to help explain water quality variations



Several attempts have been made to define the threshold concentration of biodegradable organic matter below which water can be considered biologically stable. One study (Van der Kooij et al, 1989) proposed an AOC value of 10 µg/L, and another (Servais et al, 1995) suggested a BDOC value of 0.15 mg of carbon (C) per litre. Coliform occurrences in the distribution system have also been associated with higher water biodegradable organic matter content from AOC greater than 50 (LeChevallier et al, 1991) or 100 µg/L (Volk & LeChevallier, 2000; LeChevallier et al, 1996b) and BDOC consumption in the distribution system higher than 0.15 mg C per litre (Volk & Joret, 1994). The benefits generated by reducing the biodegradable content of treated water through biological treatment have been demonstrated for the microbiological quality of water (Prévost et al, 1998) and for biofilm density (Volk & LeChevallier, 1999). Similarly, Laurent et al (1999) noted a reduction in the number of positive coliform samples in a distribution system following the installation of a nanofiltration treatment. Finally, certain lubricating oils were shown to release substantial levels of AOC into the water, which could in turn lead to increased bacterial growth (Sidorowicz, 1996; White & LeChevallier, 1993). Oil for lubricating well pumps has been associated with the occurrence of coliforms in community wells operated by a US facility (White & LeChevallier, 1993).

Pipe corrosion and corrosion control. The intensity of bacterial colonization of distribution system pipes is influenced by pipe material characteristics (Niquette et al, 2000; Verran & Hisset, 1999). It has also been shown (LeChevallier et al, 1993) that corrosion has a major impact on biofilm persistence in a chlorinated distribution system and that both the type and the rate of corrosion could affect the ability of chlorine to inactivate biofilm bacteria, including coliforms. Coliforms have been detected in corrosion tubercles (Clement et al, 1998; Emde et al, 1992; LeChevallier et al, 1987; Martin et al, 1982). A positive relationship has been found to exist between the number of miles of unlined cast-iron pipe in filtered, free-chlorinated distribution systems and coliform occurrences in the study of LeChevallier et al (1996b), suggesting that the corrosion of iron pipe surfaces is an important factor affecting coliform occurrences.

Introduction of corrosion-control mechanisms may therefore help to improve the effectiveness of chlorine disinfection, favor the presence of a chlorine residual, and enhance control of bacteria. Common mechanisms of corrosion control include increasing pH, remineralization, and the addition of phosphates or silicates. A higher pH decreases metal solubility and reduces surface corrosion. Such treatment has been successful in controlling the growth and occurrence of *Klebsiella pneumoniae* in a chlorinated distribution system (Martin et al, 1982). Pilot-scale studies (Volk et al, 2000; LeChevallier et al, 1993) showed the beneficial use of phosphate-based corrosion inhibitors to minimize the corrosion of iron pipes and its subsequent increased effectiveness on chlorine disinfection, allowing a better control of distribution system biofilms.

In a study of 31 US water utilities, LeChevallier et al (1996b) also found that the use of phosphate-based corrosion inhibitors was associated with lower coliform levels. In fact, coliform levels were 36% lower in free-chlorinated distribution systems with phosphate levels > 0.1 mg/L than in distribution systems with lower phosphate concentrations. The reduction in coliform occurrences following application of corrosion inhibitors can be explained by the fact that corrosion inhibitors reduce three things: the microbial habitat by reducing the mass of corrosion products on pipe surfaces, the adsorption capacity of iron oxides, and the disinfectant demand of existing corrosion products and the pipe surfaces (Abernathy & Camper, 1997).

Sediment accumulation in pipes. Particulate matter in a distribution system may originate from various sources, including incomplete removal of particles from raw water, release of fines from filters, precipitation of metal oxides or calcium carbonate, external contamination in pipes and reservoirs, postflocculation, biological growth, and corrosion. The sedimentation of suspended particles to form loose deposits may take place in areas with low-flow conditions (particularly in dead ends or reservoirs). The presence of coliforms in settled material in distribution systems has been shown in several studies (Lu et al, 1997; Oliver & Harbour, 1995; Schreiber & Schoenen, 1994; DeRosa, 1993). To remove sediments from water pipes, flushing programs may be undertaken by water utilities. Unidirectional flushing of the distribution system (Figure 2), in which specific sections of mains are closed in an organized and sequential manner so that water flows in a single direction from a clean to a dirty area, have been reported to generally improve water quality and diminish coliform occurrences (Antoun et al, 1999; Oliver & Pimentel, 1998).

MODELING THE OCCURRENCE OF COLIFORMS

The development of coliform predictive models has been attempted to predict, both in time and space, coliform regrowth in the distribution system. Four predictive models (Table 3) have been found in the literature and compared. These models are a combination of differential equations and/or statistical or probabilistic approaches. They usually include the influence of classical water quality parameters known to affect coliform regrowth, such as water temperature, total count of bacteria, residual chlorine, and organic matter. However, because it is known that the occurrence of coliforms in a distribution system does not result from regrowth alone, some authors (Gauthier et al, 1999b; Fang et al, 1997) have proposed the use of an alternative approach using a dynamic visualization/data-based approach that takes into account water quality data as well as many other types of parameters, such as treatment breakthrough and distribution system intrusion to explain coliform occurrence.

Coliform predictive models. ***Model based on threshold values.*** The AL.COL (Alerte coliformes) model of Volk and Joret (1994) was developed to predict coliform occurrences in the full-scale distribution systems of the Parisian suburbs, and it is based on weekly water quality monitoring data from five network sampling sites. As shown in Table 3, threshold values associated with an increased frequency of coliform occurrence have been established to define a level of risk at each sampling site resulting from the combination of the threshold values exceeded each week. Application of the model has shown that coliform occurrences were often preceded by an elevated risk (three or four positive criteria) at least one week before the coliform occurrence. During the whole study, the probability of coliform occurrence varied between 26 and 63% when the four criteria were positive, and the probability was < 1% when none of the thresholds was exceeded.

Log-logistic autoregressive multivariate model. Further studies of the Parisian suburbs' distribution systems led to the development of a log-logistic autoregressive multivariate model for the prediction of coliforms (Gatel et al, 1995). Using the same water quality parameters as the AL.COL model, the authors collected 40 to 60 samples per week from March to September for a four-year period (1992 to 1995) to develop the model. To predict the weekly percentage of coliform-positive samples on the network under study, the authors used a log-logistic autoregressive multivariate model (Table 3). The α, β, and λ parameters were estimated from the weekly values and determined using a Metropolis-Hastings–type algorithm. Results showed that the model was strongly influenced by the total direct count of bacteria, whereas temperature and chlorine appeared to be less-important factors and the consumption of organic matter could be eliminated. Model predictions (expected percentage of coliform-positive samples) for the weekly data of 1992 and 1994 were shown to correlate well with the observed values, with an R^2 coefficient of 0.75.

Tree-based statistical models. One study (LeChevallier et al, 1996a) proposed the use of a tree-based statistical model to describe how a set of predictor variables could relate to coliform occurrences in the distribution system. Classification tree models were used for unfiltered and filtered water systems, and a regression tree model was used for the general occurrence of coliforms. The tree models were developed from sampling data from 31 US water systems collected every two weeks for an 18-month period. As shown in Table 3, a larger number of variables was used to model the presence or absence of coliforms in comparison to the other existing models. The model resulted in the inclusion of a filtration step, dead-end disinfectant residual, and temperature variables. The classification rule resulted in few false-positives (i.e., samples predicted to be coliform-positive but that were in reality coliform-negative), but many false-negatives (i.e., samples predicted to be coliform-negative but that were in reality coliform-positive). A separate classification tree model for filtered systems was attempted, but the occurrence of coliforms in filtered systems was not frequent enough to apply an accurate statistical model using the cur-

TABLE 3 Coliform predictive models

	Volk & Joret, 1994	Gatel et al, 1995	LeChevallier et al, 1996a	Gale et al, 1997
Model parameters	Total coliforms; temperature (T°); total bacteria count estimated by epi-fluorescence microscopy (TDC*); total chlorine residual; consumption of biodegradable dissolved organic carbon between water treatment plant outlet and sampling point (ΔBDOC)	Total coliforms; temperature (T°); total bacteria count estimated by epifluorescence microscopy (TDC); FRC; consumption of BDOC between water treatment plant outlet and sampling point (ΔBDOC)	Total coliforms; AOC; TOC; turbidity; temperature; ammonia; nitrate; phosphate; alkalinity; hardness; disinfectant type and concentration at plant effluent, midpoints or dead ends of the system; code for filtered system or not	Total coliforms; THB—detected by pour-plate method with yeast-extract agar incubated for 24 or 48 h at 37°C or 72 h at 22°C; temperature; total chlorine residual; color, turbidity, TOC and metallic ions (infrequent records)
Model type	Threshold values: T° > 15°C; ΔBDOC > 0.15 mg/L; TDC > 5.2 log; total Cl_2 < 0.10 mg/L	Log-logistic autoregressive multivariate model: $\pi_{t+1} = f(\alpha\pi_t + \beta X_t, \lambda)$ in which π_{t+1} is the proportion of coliform-positive samples for week $t + 1$, α is the autoregressive coefficient, X_t is the variable values at time t (FRC, T°, TDC, ΔBDOC), β is the 5 coordinates vector (β_{FRC}, $\beta_{T°}$, β_{TDC}, $\beta_{\Delta BDOC}$, β_m) with β_m corresponding to a constant for the average effect, λ is the structural parameter allowing variations between log and log-logistic functions	Tree-based statistical models: Classification trees for unfiltered and filtered systems; regression tree for coliform occurrences	Generalized linear modeling method: Ln (p/ [1– p]) = $\alpha_0 + \alpha_1 \times$ Temperature + $\alpha_2 \times$ [Total chlorine] + $\alpha_3 \times$ [THB] in which p is the probability of coliform detection in a 100-mL volume and α_0, α_1, α_2, and α_3 are the constants whose values are estimated from the data
Prediction type	Level of risk—No risk: 0 or 1 threshold value exceeded; slightly exposed: 2 or 3 threshold values exceeded; exposed: 4 threshold values exceeded	Expected percentage of positive coliform samples	Definition of predictor variables for coliform occurrences	Overall number of coliform positive samples
Time of prediction	Following week	Following week	NA†	Per year
Area of prediction	At specific sampling sites	Over the entire distribution system	For the overall group of 31 distribution systems	Distribution system zones

*TDC—total direct count of bacteria, BDOC—biodegradable dissolved organic carbon, FRC—free chlorine residual, AOC—assimilable organic carbon, TOC—total organic carbon, THB—total heterotrophic bacteria
†NA—not applicable

rent methodology. A regression tree model for coliform occurrence was also developed. This model showed that in general the highest coliform occurrence rate (13.3% of positive samples) was obtained when phosphate levels (related to corrosion control) were low, the level of alkalinity was low, and the temperature was high.

Generalized linear modeling method. A regression model has been proposed by Gale et al (1997) with data collected from 13 UK water companies. The companies (divided into distribution zones) provided statutory water quality monitoring data for one or more years between 1990 and 1994 (Table 3). The authors of the study used a generalized linear modeling (GLM) method to determine the probability of coliform detection in a 100-mL water volume. However, following the validation process, because the predicted probabilities of coliform occurrence in 100-mL water samples were very low, the overall number of coliform-positive samples for groups of related zones (according to type of disinfectant used, water source, and treatment train) per year was rather established as the predicted parameter. As observed from the validation of some companies' models (between years and between similar zones in a company's distribution network), the number of positive coliform samples predicted over distribution zones was generally close to the number observed.

Advantages and limitations of the coliform predictive models. Each modeling technique used to predict coliform occurrences has its advantages and limitations. The determination of threshold values (Volk & Joret, 1994) is basic and may be considered quite simple and easy for water utilities to apply. However, the use of statistical methods for coliform prediction probably provides models that are more soundly based. The GLM method used by Gale et al (1997) is the only methodology able to identify when a model is incomplete, i.e., when modeled parameters (chlorine and total heterotrophic bacteria) are not able to fully explain differences in coliform occurrences between zones of distribution, and that further zonal information is required. Because the GLM method showed that many water company models were incomplete, it emphasized the need to consider factors other than water quality parameters to explain coliform-positive samples. The major strength of the model by Gatel et al (1995) is the inclusion of an autoregressive component that allows the prediction of the coliform-positive samples for the week to come by using the information available for the prior week and the prediction that was made for that time period. This model is the only one to take previous predictions into account.

Many limitations are associated with the use of these models. Predictions in time may vary from weekly predictions (AL.COL and log-logistic autoregressive multivariate models) to yearly predictions (Gale et al, 1997). As for the tree-based model, the authors themselves found that it clearly lacked the statistical power needed for prediction (LeChevallier et al, 1996a). Specific distribution system locations (sampling points) likely to experience coliform-positive samples are often missing. Apart from the AL.COL model, spatial prediction concerns distribution zones within a water company (Gale et al, 1997) or a whole distribution system (Gatel et al, 1995) assuming homogeneity of the variables throughout the distribution system, which is surely too simplistic. As noted by LeChevallier et al (1996a) following their examination of commonalities among 31 water systems, better predictive models could probably be obtained by examining data for individual systems. All those models predict only the presence/absence of coliforms in samples; no information is given with respect to concentration values.

Limitations associated with these models may be related to the poor content of coliform databases, because coliform occurrence rates in distribution systems are low and traditional coliform detection methods provide zero or near-zero values most of the time (Gale, 1996). Furthermore, water quality data used for model construction are usually not collected for this specific purpose, which may result in infrequent records for some parameters. Consequently, modeling coliform occurrence is quite a difficult task. The application of those models is also specific to the zones or to the distribution system where they have been calibrated, meaning that parameter optimization is necessary for each zone/distribution system with respect to local operating conditions. Few data are available on the subsequent application of those models by water utilities. In a recent study, Volk & LeChevallier (2000) proposed a variation of the AL.COL model based on three parameters (temperature, AOC, and dead-end disinfectant residual) collected for a group of distribution systems. This led to a probability of coliform occurrence of 16.1% when the three criteria were exceeded. However, it was found that the model had a low level of prediction accuracy and that further refinements were necessary to obtain more reliable results.

Dynamic visualization/data-based approach. Because water quality parameters are clearly insufficient to explain coliform occurrence in a distribution system and the parameters affecting regrowth are not completely known, identified, and measured, modeling approaches seem to have hit a wall. This has led to the use of a dynamic visualization/data-based approach to better understand water quality variations. Such an approach combines hydraulic/water quality simulation models and geographic information systems (GIS-type software), allowing the user to account for numerous parameters such as distribution system structure, operation, and maintenance as well as water quality information. The only limitation of this approach is that its effectiveness is dependent on the extent of the available databases (Barcellos, 2000; Gauthier et al, 1999b; Boulos et al, 1997; Fang et al, 1997; Pena, 1995; Deininger et al, 1992). Fang et al (1997) reported the development of a program put in place by the City of New York that integrates routine monitoring activities, hydraulic modeling, GIS software, data analysis, and special local investigations to identify and facilitate coliform problem remediation. This program has resulted in a significant decrease in coliform incidence since 1994.

Besner et al (2001) and Gauthier et al (1999b) have used an approach that combines structural, operational, and water quality parameters (Figure 3), and they were able to associate coliform recurrence in a section of the Montréal, Que., distribution system to the contamination of a large-diameter pipe with low water velocity, where breaks were reported in 1995. Improvements consisting of the addition of a visualization/exploration tool for database queries have been made to this approach by Besner et al (2000). This was done to facilitate the study of the impact of distribution system interventions on water quality.

Because coliform occurrence may be triggered by various factors and these factors are not easily quantifiable, it seems unrealistic to try to predict short-term, localized contamination. It is thus more important to improve our understanding of coliform occurrence so that we will eventually be able to quantify the parameters involved. The consideration of multiple databases—combined with their visualization—is a key element in this process.

Modeling perspectives. The use of artificial neural network (ANN) models could constitute a new research avenue for coliform prediction. ANNs have the capacity to learn from examples and to generalize to previously unseen data, as well as the ability to handle nonlinear relationships. At this time, this type of model has not been used extensively in the field of drinking water treatment and distribution. Rodriguez & Sérodes (1996) used an ANN modeling approach to estimate the disinfectant dose adjustments required during water rechlorination in storage tanks, and Skipworth et al (1999) predicted the oxidation reduction potential at single and multiple points within a distribution system. Moreover, using ANNs for coliform prediction would require large databases for building strong models, and, as long as coliform data show values below detection levels or zero values, ANN model development will be difficult. In fact, this is probably true for any type of model. As an alternative, the use of atypical bacteria (i.e., noncoliform bacteria on m-Endo agar) as a supplemental indicator group could be considered, as suggested by Brion et al (2000). That study successfully used atypical bacteria and ANNs for pollution ranking and source identification in a surface water reservoir. The development of more "sensitive" coliform detection methods that would yield other than zero values could also help support the building of such models.

SUMMARY AND CONCLUSIONS

Obviously, distribution systems play a major role in maintaining the quality of treated water. Detection of coliform organisms in a distribution system may result from multiple factors and not only from the type of contamination (treatment breakthrough/intrusion). Coliform occurrence may be greatly affected by the following distribution system features:

• The hydraulics influence the transport of contaminants, the deposition/resuspension of particulate material, the residence time of the water in the system, and the occurrence of low pressure.

REFERENCES

Abernathy, C.G. & Camper, A., 1997. Interactions Between Pipe Materials, Disinfectants, Corrosion Inhibitors, Organics, and Distribution Biofilms. Proc. 1997 AWWA WQTC, Denver.

American Backflow Prevention Association, 1995 (4th ed.). *Summary of Backflow Incidents.* www.abpa.org/pnw-awwa.htm (accessed 2001).

Antoun, E.N. et al, 1999. Unidirectional Flushing: A Powerful Tool. *Jour. AWWA,* 91:7:62.

Archibald, F., 2000. The Presence of Coliform Bacteria in Canadian Pulp and Paper Mills Systems—A Cause for Concern? *Water Quality Res. Jour. Canada,* 35:1:1.

Barcellos, C., 2000. Health Risk Analysis of the Rio de Janeiro Water Supply Using Geographical Information Systems. *IAHS Publications—Series of Proceedings and Reports,* 260:95.

Berman, D. et al, 1988. Inactivation of Particle-associated Coliforms by Chlorine and Monochloramine. *Applied & Envir. Microbiol.,* 54:2.507.

Besner, M-C. et al, 2001. Understanding Distribution System Water Quality. *Jour. AWWA,* 93:7:101.

Besner, M.-C. et al, 2000. Identification of the Causes for Coliforms and Water Quality Complaints in Distribution Systems: An Event-based Approach. Proc. 2000 AWWA WQTC, Salt Lake City.

Boulos, P.F. et al, 1997. Water Distribution Network Management: A Fully Integrated Approach. *Jour. NEWWA,* 111:6:180.

Brazos, B.J. & O'Connor, J.T., 1996. Seasonal Effects on Generation of Particle-associated Bacteria During Distribution. *Jour. Envir. Engrg.,* 122:12:1050.

Brion, G.M. et al, 2000. New Approach to Use of Total Coliform Test for Watershed Management. *Water Sci. & Technol.,* 42:1:65.

Camper, A., 1996. *Factors Limiting Microbial Growth in Distribution Systems: Laboratory and Pilot-scale Experiments.* AWWA Res. Fdn., Denver.

Camper, A.K. et al, 1997. Comparison of Free Chlorine and Monochloramine for the Control of Biofilms in Model Distribution System Biofilms. Proc. 1997 AWWA WQTC, Denver.

Camper, A.K., 1995. Factors Influencing Biofilm Growth in Drinking Water Distribution Systems. Doctoral thesis, Montana State Univ., Bozeman, Mont.

Camper, A.K. et al, 1986. Bacteria Associated With Granular Activated Carbon Particles in Drinking Water. *Applied & Envir. Microbiol.,* 52:3:434.

Camper, A.K. et al, 1985. Growth and Persistence of Pathogens on Granular Activated Carbon Filters. *Applied & Envir. Microbiol.,* 50:6:1378.

Chalmers, R.M. et al, 2000. Waterborne *Escherichia coli* O157. *Jour. Applied Microbiol.,* 88:124S.

Clark, R.M. et al, 1999. Water Quality and the Replacement and Repair of Drinking Water Infrastructure: The Washington, D.C., Case Study. *Jour. Water SRT—Aqua,* 48:3:106.

Clark, R.M. et al, 1996. Tracking a *Salmonella serovar typhimurium* Outbreak in Gideon, Missouri: Role of Contaminant Propagation Modeling. *Jour. Water SRT—Aqua,* 45:4:171.

Clement, J.A. et al, 1998. Analyses and Interpretation of the Physical, Chemical, and Biological Characteristics of Distribution System Pipe Scales. Proc. 1998 AWWA WQTC, San Diego.

Colbourne, J.S. et al, 1991. The Operational Impact of Growth of Coliforms in London's Distribution System. Proc. 1991 AWWA WQTC, Orlando, Fla.

Craddock, J.L. & Castle, R.G., 1997. Viable But Injured Coliforms in Drinking Water Supplies. *Coliforms and* E. coli*: Problem or Solutions?* Special Publications of the Royal Soc. of Chemistry, 191:182.

Craun, G.F. & Calderon, R.L., 2001. Waterborne Disease Outbreaks Caused by Distribution System Deficiencies. *Jour. AWWA,* 93:9:64.

Craun G.F. & Calderon R.L., 1999 (1st ed). Waterborne Disease Outbreaks: Their Causes, Problems, and Challenges to the Treatment Barriers. *Waterborne Pathogens.* AWWA Manual M48, AWWA, Denver.

Craun, G.F. et al, 1997. Coliform Bacteria and Waterborne Disease Outbreaks. *Jour. AWWA,* 89:3:96.

Deininger, R.A. et al, 1992. Animation and Visualization of Water Quality in Distribution Systems. *Jour. AWWA,* 84:7:48.

DeRosa, S., 1993. Loose Deposits in Water Mains. Report DoE 3118-/2, Dept. of the Envir., London.

Ding, G. et al, 1995. Effect of Disinfection on the Survival of *Escherichia coli* Associated With Nematoda in Drinking Water. *Water Supply,* 13:3:101.

Dubay, C., 1997. The Pressure's Building. *NFPA Jour.,* 91:4:68.

Duranceau, S.J. et al, 1998. *Impact of Wet-pipe Fire Sprinkler Systems on Drinking Water Quality.* AWWA Res. Fdn., Denver.

Edberg S.C. et al, 2000. *Escherichia coli*: The Best Biological Drinking Water Indicator for Public Health Protection. *Jour. Applied Microbiol.,* 88:106S.

• Physical characteristics, such as elevated water temperatures, were shown to often be related to coliform detection.

• Chemical characteristics, such as the type and concentration of disinfectant used in the system and the level of biodegradable organic matter, have also been related by many authors to coliform occurrence.

• Structural properties, such as pipe material, may constitute the principal influence on the degree of corrosion and the rates of pipe breakage and leakage that will be found in the system.

The effects of some of these factors on coliform occurrence are common to all distribution systems, whereas others are more site-specific. However, taken as a whole, all these factors will affect the capability of coliforms to survive in a distribution system. Because of the transport/deposition/survival mechanisms occurring in the distribution system, the signal of bacterial contamination entering the system may consequently be biased, so that it becomes very difficult in some cases to detect contamination directly at its point of entrance or at the time it penetrated the system. Such situations imply that water utilities and authorities are probably failing to detect numerous contamination events in their systems and that those that are detected are often difficult to explain.

Understanding the origins of coliform occurrence in a distribution system, which are usually not very obvious,

Edberg, S.C. et al, 1994. Differentiation of Distribution Systems, Source Water, and Clinical Coliforms by DNA Analysis. *Jour. Clinical Microbiol.,* 32:1:139.

Emde, K.M. et al, 1992. Initial Investigation of Microbially Influenced Corrosion (MIC) in a Low-temperature Water Distribution System. *Water Res.,* 26:2:169.

Fang, M. et al, 1997. Development of an Enhanced Water Quality Monitoring Program for Coliform Control. Proc. 1997 AWWA WQTC, Denver.

Fass, S. et al, 1996. Fate of *Escherichia coli* Experimentally Injected Into a Drinking Water Distribution Pilot System. *Water Res.,* 30:9:2215.

Fokken, B. et al, 1998. Raw Water Protection and High Standard in Pipe Network Enables Cologne Municipal Water Supply to Cease Disinfection. *Water Supply,* 16:1:543.

Furtado C. et al, 1998. Outbreaks of Waterborne Infectious Disease in England and Wales, 1992–95. *Epidemiol. Infect.,* 121:1:109.

Gale, P. et al, 1997. The Development and Application of Coliform Predictive Models for the UK Water Industry. *Jour. Water SRT—Aqua,* 46:4:185.

Gale, P., 1996. Coliforms in the Drinking Water Supply: What Information Do the 0/100 mL Samples Provide? *Jour. Water SRT—Aqua,* 45:4:155.

Gatel, D. et al, 2000. Microbiological Water Quality Management in the Paris Suburbs' Distribution System. *Jour. Water SRT—Aqua,* 49:5:231.

Gatel, D. et al, 1995. Forecasting the Number of Coliform-positive Samples. Proc. 1995 AWWA WQTC, New Orleans.

Gauthier, V. et al, 1999a. Chlorine Inactivation of *Sphingomonas* Cells Attached to Goethite Particles in Drinking Water. *Applied & Envir. Microbiol.,* 65:1:355.

Gauthier, V. et al, 1999b. Understanding the Microbial Quality of Drinking Water Using Distribution System Structure Information and Hydraulic Modeling. Proc. 1999 AWWA WQTC, Tampa, Fla.

Gauthier, V. et al, 1997. How Good Are Water Distribution Systems for Transport of Particulate Matter? Proc. 1997 AWWA WQTC, Denver.

Geldreich, E.E., 1996. Pathogenic Agents in Freshwater Resources. *Hydrological Processes,* 10:2:315.

Geldreich, E.E. et al, 1992. Searching for a Water Supply Connection in the Cabool, Missouri, Disease Outbreak of *Escherichia coli* O157:H7. *Water Res.,* 26:8:1127.

Gueco, M.C.B. et al, 1999. Achieving Total Coliform MCLG Zero in a Large-scale Chloraminated Distribution System. Proc. 1999 AWWA WQTC, Tampa, Fla.

Haas, C.N. et al, 1999. *Development of Disinfection Guidelines for the Installation and Replacement of Water Mains.* AWWA Res. Fdn., Denver.

Häfliger, D. et al, 2000. Outbreak of Viral Gastroenteritis Due to Sewage-contaminated Drinking Water. *Int. Jour. Food. Microbiol.,* 54:1:123.

Health-Canada, 2000. Waterborne Outbreak of Gastroenteritis Associated With a Contaminated Municipal Water Supply, Walkerton, Ont., May–June 2000. www.hc-sc.gc.ca/hpb/lcdc/publicat/ccdr/00vol26/dr2620eb.html.

Herrick, D., 1997. Cross Connections and Backflow. *Water Well Jour.,* 51:5:67.

Herson, D.S. et al, 1987. Attachment as a Factor in the Protection of *Enterobacter cloacae* From Chlorination. *Applied & Envir. Microbiol.,* 53:5:1178.

Holt, D.M. et al, 1995. Devising Practical Operational Strategies to Control Biofilm Growth in London's Water Distribution System. Proc. 1995 AWWA WQTC, New Orleans.

Huck, P.M., 1990. Measurement of Biodegradable Organic Matter and Bacterial Growth in Drinking Water. *Jour. AWWA,* 82:7:78.

Hudson, L.D. et al, 1983. Coliforms in a Water Distribution System: A Remedial Approach. *Jour. AWWA,* 75:11:564.

Jackson, S.G. et al, 1998. *Escherichia coli* O157:H7 Diarrhoea Associated With Well Water and Infected Cattle on an Ontario Farm. *Epidemiol. Infect.,* 120:1:17.

Jones, K. & Bradshaw, S.B., 1996. Biofilm Formation by the *Enterobacteriaceae:* A Comparison Between *Salmonella enteridis, Escherichia coli,* and a Nitrogen-fixing Strain of *Klebsiella pneumoniae. Jour. Applied Bacteriol.,* 80:4:458.

Kiéné, L. et al, 1999. Limit and Benefit of Chlorine Residuals for Water Quality Management in Drinking Water Distribution Systems: What Is the Right Chlorine Residual? Proc. 1999 AWWA Ann. Conf., Chicago.

King, C.H. et al, 1988. Survival of Coliforms and Bacterial Pathogens Within Protozoa During Chlorination. *Applied & Envir. Microbiol.,* 54:12:3023.

Kirmeyer, G. et al, 2000. *Guidance Manual for Maintaining Distribution System Water Quality.* AWWA Res. Fdn., Denver.

Kirmeyer, G. et al, 1999. Pathogen Intrusion Into the Distribution System. Proc. 1999 AWWA WQTC, Tampa, Fla.

Klein, H.-P. & Forster, R., 1999. Network Operation Without Safety Chlorination in Zürich. *Jour. Water SRT—Aqua,* 48:2:53.

is the first step toward a permanent solution to the problem. In some cases, improvements in water treatment and network management have allowed water utilities to solve their problems without determining the source of coliforms in their systems (Clark et al, 1999). The application of measures such as reducing the nutrient level entering the distribution system, reducing water residence time in the network, applying a chloramine residual, as well as methods to control pipe corrosion and unidirectional flushing, have shown in many cases to be quite effective in reducing coliform occurrence (Kirmeyer et al, 2000; USEPA, 1999).

Replacing total coliforms by *E. coli* as the indicator, as proposed by Edberg et al (2000), would perhaps lead to a stronger link between health risk and regulatory failure. Yet it also would result in a major reduction in coliform-positive events, further reducing the potential for determining the source of the fecal contamination. Moreover, predictive models for failures would be even more difficult to build because of the small number of positive samples. In such a case, total coliforms could be kept as the operational parameter used by utilities to evaluate regrowth phenomena or nonfecal contamination while being removed from the assessment of compliance issues (Stevens et al, 2001).

The prediction of noncompliant samples seems difficult, if not impossible, because the number of possible causes for coliform occurrence is high and coliform

Kreft, P. et al, 1985. Converting From Chlorine to Chloramines: A Case Study. *Jour. AWWA,* 77:1:38.

Kreig, N.R., 1984. *Bergey's Manual of Systematic Bacteriology.* Vol. 1. (Williams & Wilkins, editors), Williams & Wilkins, Baltimore.

Kukkula, M. et al, 1997. Waterborne Outbreak of Viral Gastroenteritis. *Scand. Jour. Infect. Dis.,* 29:4:415.

Lahti, K. & Hiisvirta, L., 1995. Causes of Waterborne Outbreaks in Community Water Systems in Finland: 1980–1992. *Water Sci. & Technol.,* 31:5:33.

Laurent, P. et al, 1999. Microbiological Quality Before and After Nanofiltration. *Jour. AWWA,* 91:10:62.

LeChevallier, M.W., 1999. The Case for Maintaining a Disinfectant Residual. *Jour. AWWA,* 91:1:86.

LeChevallier, M.W., 1990. Coliform Regrowth in Drinking Water: A Review. *Jour. AWWA,* 82:11:74.

LeChevallier, M.W. et al, 1999. Pathogen Intrusion Into Potable Water. Proc. 1999 AWWA WQTC, Tampa, Fla.

LeChevallier, M.W. et al, 1996a. *Factors Limiting Microbial Growth in Distribution Systems: Full-scale Experiments.* AWWA Res. Fdn., Denver.

LeChevallier, M.W. et al, 1996b. Full-scale Studies of Factors Related to Coliform Regrowth in Drinking Water. *Applied & Envir. Microbiol.,* 62:7:2201.

LeChevallier, M.W. et al, 1993. Examining the Relationship Between Iron Corrosion and the Disinfection of Biofilm Bacteria. *Jour. AWWA,* 85:7:111.

LeChevallier, M.W. et al, 1991. Bacterial Nutrients in Drinking Water. *Applied & Envir. Microbiol.,* 57:3:857.

LeChevallier, M.W. et al, 1990. Disinfecting Biofilms in a Model Distribution System. *Jour. AWWA,* 82:7:87.

LeChevallier, M.W. et al, 1987. Examination and Characterization of Distribution System Biofilms. *Applied & Envir. Microbiol.,* 53:12:2714.

LeChevallier, M.W. & McFeters, G.A., 1985. Interactions Between Heterotrophic Plate Count Bacteria and Coliform Organisms. *Applied & Envir. Microbiol.,* 49:5:1338.

Lévi, Y. et al, 1992. Étude d'un Réseau à Très Faible Teneur en Matière Organique Biodégradable: Le Réseau de la Ville de Nice. *Sci. Eau,* 5:225.

Levy, R.V. et al, 1986. Occurrence and Public Health Significance of Invertebrates in Drinking Water Systems. *Jour. AWWA,* 78:9:105.

Lu, L. et al, 1997. In-situ Water Main Biological Study in New York City. Proc. 1997 AWWA WQTC, Denver.

Ludwig, F. et al, 1985. Detection of Elevated Levels of Coliform Bacteria in a Public Water Supply—Connecticut. *Morbidity & Mortality Weekly Rept.,* 34:10:142.

Lupi, E. et al, 1995. Recovery of Bacteria in Nematodes Isolated From a Drinking Water Supply. *Jour. Water SRT—Aqua,* 44:5:212.

Marret, L.D. & King, W.D., 1995. Great Lakes Basin Cancer Risk Assessment : A Case-control Study of Cancers of the Bladder, Colon, and Rectum. Research report prepared for the Bureau of Chronic Disease. Epidemiology, Laboratory Centre for Disease Control, Health-Canada, Toronto.

Martin, R.S. et al, 1982. Factors Affecting Coliform Bacteria Growth in Distribution Systems. *Jour. AWWA,* 74:1:34.

Mathieu, L. et al, 1992. Paramètres Gouvernant la Prolifération Bactérienne Dans les Réseaux de Distribution. *Sci. Eau,* 5:91.

McFeters, G.A., 1990. Enumeration, Occurrence, and Significance of Injured Indicator Bacteria in Drinking Water. *Drinking Water Microbiology.* Springer-Verlag Inc., New York.

McFeters, G.A. et al, 1986. Injured Coliforms in Drinking Water. *Applied & Envir. Microbiol.,* 51:1:1.

McMath, S.M. & Casey, R.J., 2000. The Use of Network Modeling Techniques to Resolve Water Quality Issues in Distribution Systems. Proc. 2000 AWWA WQTC, Salt Lake City.

McMath, S.M. et al, 1999. The Fate of Environmental Coliforms in a Model Water Distribution System. *Letters in Applied Microbiol.,* 28:2:93.

Miettinen, I.T. et al, 1997. Phosphorus and Bacterial Growth in Drinking Water. *Applied & Envir. Microbiol.,* 63:8:3242.

Mitcham, R.P. et al, 1983. Free Chlorine Versus Ammonia–Chlorine: Disinfection, Trihalomethane Formation, and Zooplankton Removal. *Jour. AWWA,* 75:4:196.

Momba, M.N.B. et al, 1999. Examination of the Behavior of *Escherichia coli* in Biofilms Established in Laboratory-scale Units Receiving Chlorinated and Chloraminated Water. *Water Res.,* 33:13:2937.

Montiel, A. & Welté, B., 1999. L'Affinage de l'Eau par Filtration sur Charbon Actif en Grains. Les Contraintes Imposées par Cette Étape de Traitement. *TSM, Génie Urbain—Génie Rural,* 9:49.

Morin, P. et al, 1999. Bacterial Resistance to Chlorine Through Attachment to Particles and Pipe Surfaces in Drinking Water Distribution Systems. *Biofilms in*

detection is biased by transport and survival mechanisms in the distribution system, which are difficult to quantify. Therefore, greater understanding of coliform occurrence is needed to eventually enable quantification of the parameters involved. Because the tools currently available are not adequate, the development of new approaches, which should involve the consideration of multiple databases, is essential. This is critical because water quality information is necessary, but often not wholly sufficient, to explain coliform occurrence in a distribution system. All types of databases (operation and maintenance, hydraulic, and so forth) should be made available to increase the chances of identifying coliform problems. Because our capacity to explain and predict is also strongly influenced by the results obtained by the coliform detection methods that "unfortunately" give zero values in 90 to > 99% of the cases, it is also suggested that new methods allowing for higher values be accepted with a view to understanding, but not regulating, coliform presence. The combination of a more effective detection method and an analytical tool integrating a variety of parameters should greatly help water utilities in identifying the causes of water quality problems and, consequently, allow them to apply corrective measures to eliminate coliform occurrence from their distribution systems.

ACKNOWLEDGMENT

This article was part of the research project "A Comprehensive Approach for Controlling Coliforms in Drinking Water Distribution Systems," funded by Vivendi Water–US Filter, as part of a global initiative to improve

the Aquatic Environment (C.W. Keevil et al, editors). Royal Soc. of Chemistry, Cambridge, U.K.

Morissette, C. et al, 1999. La Qualité de l'Eau Potable à Laval: Un Programme Intégré axé sur la Prévention. Proc. Conf. Réseau- Environnement—11e Atelier Sur l'Eau Potable, Longueuil, Que.

Niquette, P. et al, 2000. Impacts of Pipe Materials on Densities of Fixed Bacterial Biomass in a Drinking Water Distribution System. *Water Res.,* 34:6:1952.

Norton, C.D. & LeChevallier, M.W., 1997. Chloramination: Its Effect on Distribution System Water Quality. *Jour. AWWA,* 89:7:66.

Norton, C. et al, 1995. Implementation of Chloramination and Corrosion Control to Limit Microbial Activity in the Distribution System. Proc. 1995 AWWA WQTC, New Orleans.

Oliver, E.D. & Pimentel, R., 1998. Reduction of Coliforms in Sediments Indicates Flushing Program Success. Proc. 1998 AWWA WQTC, San Diego.

Oliver, E.D. & Harbour, J.D., 1995. Speciation of Total Coliforms Isolated From Sediments in Brown Water Released During a Flushing Program Undertaken by the Seattle Water Department. Proc. 1995 AWWA WQTC, New Orleans.

Olstadt, J.M. et al, 1998. A Study of the Seasonal Occurrence of Total Coliform Bacteria Positivity in Drinking Water. Proc. 1998 AWWA WQTC, San Diego.

O'Neill, J.G. & Parry, O.T., 1997. The Operational Significance of Coliform Species in Treated Water. *Coliforms and* E. coli*: Problem or Solutions?* Special Publications of the Royal Society of Chemistry, 191:249.

Paquin, J.L. et al, 1992. Effet du Chlore sur la Colonisation Bactérienne d'un Réseau Expérimental de Distribution d'Eau. *Sci. Eau,* 5:399.

Parent, A. et al, 1996. Control of Coliform Growth in Drinking Water Distribution Systems. *Jour. CIWEM,* 10:6:442.

Payment, P. et al, 1997. A Prospective Epidemiological Study of Gastrointestinal Health Effects Due to the Consumption of Drinking Water. *Intl. Jour. Envir. Health,* 7:5.

Payment, P. et al, 1991. A Randomized Trial to Evaluate the Risk of Gastrointestinal Disease Due to the Consumption of Drinking Water Meeting Currently Accepted Microbiological Standards. *Amer. Jour. Public Health,* 81:703.

Pena, S., 1995. A Geographic Information System for Monitoring Water Quality in the Distribution Network. *Water Supply,* 13:3:77.

Pizzi, N., 1996. Optimizing Distribution System Operations. *Opflow,* 22:11:1.

Pontius, F.W., 2000. Reconsidering the Total Coliform Rule. *Jour. AWWA,* 92:2:14.

Prévost, M. et al, 1998. Suspended Bacterial Biomass and Activity in Full-scale Drinking Water Distribution Systems: Impact of Water Treatment. *Water Res.,* 32:5:1393.

Raina, P.S. et al, 1999. The Relationship Between *E. coli* Indicator Bacteria in Well Water and Gastrointestinal Illnesses in Rural Families. *Can. Jour. Public Health,* 90:3:172.

Ridgway, H.F. & Olson, B.H., 1982. Chlorine Resistance Patterns of Bacteria From Two Drinking Water Distribution Systems. *Applied & Envir. Microbiol.,* 44:4:972.

Rodriguez, M.J. & Sérodes, J.-B., 1996. Neural Network-based Modelling of the Adequate Chlorine Dosage for Drinking Water Distribution. *Can. Jour. Civ. Engrg.,* 23:3:621.

Sathasivan, A. et al, 1997. Role of Inorganic Phosphorus in Controlling Regrowth in Water Distribution System. *Water Sci. & Technol.,* 35:8:37.

Schoenen, D. & Hoyer, O., 2000. Contamination of Drinking Water With Coliform Organisms by the Larvae of Gnats in the Water Treatment Plant. *Acta Hydrochim. Hydrobiol.,* 28:1:47.

Schreiber, H. et al, 1997. Invertebrate Colonization of Granular Activated Carbon Filters. *Water Res.,* 31:4:743.

Schreiber, H. & Schoenen, D., 1994. Chemical, Bacteriological, and Biological Examination and Evaluation of Sediments From Drinking Water Reservoirs—Results From the First Sampling Phase. *Zentralbl. Hyg. Umweltmed,* 196:2:153.

Schreppel, C.K. & Geiss, A.J., 1996. Total Coliform Occurrence and Corrosion Control. Proc. National Conf. on Integrating Corrosion Control and Other Water Quality Goals, Cambridge, Mass.

Semenza, J.C. et al, 1998. Water Distribution System and Diarrheal Disease Transmission: A Case Study in Uzbekistan. *Amer. Jour. Trop. Med. Hyg.,* 59:6:941.

Servais, P. et al, 1995. Comparison of the Bacterial Dynamics in Various French Distribution Systems. *Jour. Water SRT—Aqua,* 44:1:10.

Servais, P. et al, 1992. Studies of BDOC and Bacterial Dynamics in the Drinking Water Distribution System of the Northern Parisian Suburbs. *Sci. Eau,* 5:69.

water quality in distribution systems. The authors thank B. Barbeau for his helpful review of a previous version of the manuscript.

ABOUT THE AUTHORS:

Marie-Claude Besner[1] *is a research associate with École Polytechnique de Montréal, NSERC Industrial Chair on Drinking Water, Civil, Geological, and Mining Engineering, CP 6079, Succ. Centre-ville, Montréal, PQ, Canada, H3C 3A7; e-mail marie-claude.besner@polymtl.ca. She received her master's degree in applied sciences from École Polytechnique and has been previously published in* JOURNAL AWWA *and* Journal of Water Resources Planning and Management. *Vincent Gauthier is also a research associate with École Polytechnique de Montréal. Pierre Servais is associate professor with Université Libre de Bruxelles in Brussels, Belgium. Anne Camper is associate professor with Montana State University, Center for Biofilm Engineering, Bozeman, Mont.*

FOOTNOTE

[1]To whom correspondence should be addressed

If you have a comment about this article, please contact us at journal@awwa.org.

Sibille, I. et al, 1997. Behavior of Accidental Contamination in Drinking Water Distribution Systems. Proc. 1997 AWWA WQTC, Denver.

Sidorowicz, S.V., 1996. The Microbiology of Lubricants and Oils for Water Supply Applications. *Jour. CIWEM,* 10:3:205.

Skipworth, P.J. et al, 1999. Predicting Water Quality in Distribution Systems Using Artificial Neural Networks. Proc. Instn. Civ. Engrs. Wat., Marit. & Energy, 136:1.

Snead, M.C. et al, 1980. The Effectiveness of Chlorine Residuals in Inactivation of Bacteria and Viruses Introduced by Posttreatment Contamination. *Water Res.,* 14:403.

Song, D.J. et al, 1998. Maintenance of Free Chlorine and Chloramine Residual in EBMUD Distribution System Pipelines and Storage Reservoirs. Proc. 1998 AWWA WQTC, San Diego.

Standridge, J. et al, 1995. Characterization of *E. coli* and Total Coliform Organisms Isolated From Wisconsin Waters and Reassessment of Their Public Health Significance. Proc. 1995 AWWA WQTC, New Orleans.

Stevens, M. et al, 2001. Microbial Indicators of Water Quality—An NHMRC Discussion Paper. Public Consultation Draft—Sept. 2001. <www.nhmrc.health.gov.au>.

Stringfellow, W.T. et al, 1993. Enumerating and Disinfecting Bacteria Associated With Particles Released From GAC Filters-Adsorbers. *Jour. AWWA,* 85:9:70.

Te Welscher, R.A.G. et al, 1998. Experiences With 15 Years of Drinking Water Distribution Without a Chlorine Residual. *Water Supply,* 16:3:153.

Trussell, R.R., 1999. An Overview of Disinfectant Residuals in Drinking Water Distribution Systems. *Jour. Water SRT—Aqua,* 48:1:2.

USEPA, 1999. Microbial and Disinfection Byproduct Rules Simultaneous Compliance Guidance Manual. EPA 815-R-99-015. Ofce. of Water, Washington.

USEPA, 1997. Community Water Systems Survey—Vol. I & II; Overview. EPA 815-R-97-001a, -001b. Ofce. of Water, Washington.

USEPA, 1989. Total Coliforms. Final Rule. *Fed. Reg.,* 54:124:27544 (June 29, 1989).

Van der Kooij, D. et al, 1999. Maintaining Quality Without a Disinfectant Residual. *Jour. AWWA,* 91:1:55.

Van der Kooij, D. et al, 1995. Multiple Barriers Against Microorganisms in Water Treatment and Distribution in the Netherlands. *Water Supply,* 13:2:13.

Van der Kooij, D. et al, 1989. The Effects of Ozonation, Biological Filtration and Distribution on the Concentration of Easily Assimilable Organic Carbon (AOC) in Drinking Water. *Ozone Sci. Engrg.,* 11:297.

Van der Wende, E. & Characklis, W.G., 1990. Biofilms in Potable Water Distribution Systems. *Drinking Water Microbiology* (G.A. McFeters, editor). Springer-Verlag, New York.

Van Lieverloo, H., 1997. How to Control Invertebrates in Distribution Systems: By Starvation or by Flushing? Proc. 1997 AWWA WQTC, Denver.

Verran, J. & Hissett, T., 1999. The Effect of Substratum Surface Defects Upon Retention of, and Biofilm Formation by Microorganisms From Potable Water. *Biofilms in the Aquatic Environment* (C.W. Keevil et al, editors). Royal Soc. of Chemistry, Cambridge, U.K.

Volk, C. et al, 2000. Practical Evaluation of Iron Corrosion Control in a Drinking Water Distribution System. *Water Res.,* 34:6:1967.

Volk, C.J. & LeChevallier, M.W., 2000. Assessing Biodegradable Organic Matter. *Jour. AWWA,* 92:5:64.

Volk, C.J. & LeChevallier, M.W., 1999. Impacts of the Reduction of Nutrient Levels on Bacterial Water Quality in Distribution Systems. *Applied & Envir. Microbiol.,* 65:11:4957.

Volk, C. & Joret, J.-C., 1994. Paramètres Prédictifs de l'Apparition des Coliformes dans les Réseaux de Distribution d'Eau d'Alimentation. *Sci. Eau,* 7:131.

Warburton D. et al, 1998. A Further Review of the Microbiological Quality of Bottled Water Sold in Canada: 1992–1997 Survey Results. *Intl. Jour. Food. Microbiol.,* 39:3:221.

White, D.R. & LeChevallier, M.W., 1993. AOC Associated With Oils for Lubricating Well Pumps. *Jour. AWWA,* 85:8:112.

WHO (World Health Organization), 1993 (2nd ed.). *Guidelines for Drinking Water Quality. Vol. 1—Recommendations.* WHO, Geneva.

Wierenga, J.T., 1985. Recovery of Coliforms in the Presence of a Free Chlorine Residual. *Jour. AWWA,* 77:11:83.

Wilczak, A. et al, 1996. Occurrence of Nitrification in Chloraminated Distribution Systems. *Jour. AWWA,* 88:7:74.

Yarze, J.C. & Chase, M.P., 2000. *E. coli* O157:H7—Another Waterborne Outbreak. *Amer. Jour. Gastroenterol.,* 95:4:1096.

Zmirou, D. et al, 1995. Residual Microbiological Risk After Simple Chlorine Treatment of Drinking Ground Water in Small Community Systems. *European Jour. Public Health,* 5:2:75.