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Full-Scale Studies of Factors Related to Coliform Regrowth in Drinking Water

MARK W. LECHEVALLIER,[1]* NANCY J. WELCH,[1] AND DARRELL B. SMITH[2]

American Water Works Service Company, Inc., Voorhees, New Jersey 08043,[1] and Regional Water Authority, New Haven, Connecticut 06511-5966[2]

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An 18-month survey of 31 water systems in North America was conducted to determine the factors that contribute to the occurrence of coliform bacteria in drinking water. The survey included analysis of assimilable organic carbon (AOC), coliforms, disinfectant residuals, and operational parameters. Coliform bacteria were detected in 27.8% of the 2-week sampling periods and were associated with the following factors: filtration, temperature, disinfectant type and disinfectant level, AOC level, corrosion control, and operational characteristics. Four systems in the study that used unfiltered surface water accounted for 26.6% of the total number of bacterial samples collected but 64.3% (1,013 of 1,576) of the positive coliform samples. The occurrence of coliform bacteria was significantly higher when water temperatures were >15°C. For filtered systems that used free chlorine, 0.97% of 33,196 samples contained coliform bacteria, while 0.51% of 35,159 samples from chloraminated systems contained coliform bacteria. The average density of coliform bacteria was 35 times higher in free-chlorinated systems than in chloraminated water (0.60 CFU/100 ml for free-chlorinated water compared with 0.017 CFU/100 ml for chloraminated water). Systems that maintained dead-end free chlorine levels of <0.2 mg/liter or monochloramine levels of <0.5 mg/liter had substantially more coliform occurrences than systems that maintained higher disinfectant residuals. Free-chlorinated systems with AOC levels greater than 100 μg/liter had 82% more coliform-positive samples and 19 times higher coliform levels than free-chlorinated systems with average AOC levels less than 99 μg/liter. Systems that maintained a phosphate-based corrosion inhibitor and limited the amount of unlined cast iron pipe had fewer coliform bacteria. Several operational characteristics of the treatment process or the distribution system were also associated with increased rates of coliform occurrence. The study concludes that the occurrence of coliform bacteria within a distribution system is dependent upon a complex interaction of chemical, physical, operational, and engineering parameters. No one factor could account for all of the coliform occurrences, and one must consider all of the parameters described above in devising a solution to the regrowth problem.

The occurrence of coliform bacteria in treated water supplies is the most common reason for the violation of federal and state drinking water standards (47). Traditionally, the presence of coliform bacteria in drinking water has been viewed as an indicator of fecal contamination through a cross connection, inadequate treatment, or an inability to maintain a disinfectant residual in distributed water. In the concept of an ideal fecal indicator, the sentinel organism does not grow outside of the intestinal tract. The recognition that indicator microorganisms grow in finished drinking water supplies is not new. In 1930, the American Water Works Association Committee on Water Supply reported on the problem of regrowth of *Bacillus coli* in drinking water systems (8). In 1937, Adams and Kingsbury described bacteriological problems that stemmed from bacterial growths in the pipe network; apparently, the finished water at the point of entry was free of indicator bacteria (1). However, with increasingly stringent water quality standards, the problem of regrowth of coliform bacteria has become of paramount importance. For a water system that collects 40 samples per month, 2 coliform organisms could result in a violation of the Total Coliform Regulation (18).

In recognition that regrowth of coliform bacteria occurs in finished drinking water and may not be related to fecal or pathogen contamination or to waterborne disease, the U.S. Environmental Protection Agency has developed criteria by which a variance to the Total Coliform Rule could be granted (19). As part of these criteria, utilities must develop a plan by which they can control coliform regrowth within the pipe network and bring the system back into compliance. The problem is that the factors controlling the regrowth of bacteria in distribution systems are not well understood, and there is no proven plan that utilities can adopt that can ensure that compliance with the Total Coliform Rule can be achieved.

The objective of this study was to determine the chemical, physical, and operational factors that influence the occurrence of coliform bacteria in finished drinking water systems. We examined 31 full-scale systems in North America to determine the factors associated with the occurrence of coliform bacteria in drinking water.

MATERIALS AND METHODS

Site selection. The sites included in this study were known to experience episodes of coliform occurrences (47). The 31 systems studied were located in 22 states and one Canadian province (Fig. 1). Tables 1 to 3 summarize the raw water, treatment, and distribution system characteristics of the systems. Overall, 14 systems used lakes or reservoirs for source water, and 16 systems used river water (the source for one system was aqueduct water). These supplies ranged from fully protected to heavily polluted, and average raw water fecal coliform levels varied from 0 to 6,500 CFU/100 ml (Table 1). Daily production rates ranged between 3 and 420 million gallons per day (1 gal = 3.785 liters) from treatment plants that included unfiltered surface water, direct filtration, slow sand filtration, softening, conventional plants with mono- or dual-medium filtra-

* Corresponding author. Mailing address: American Water Works Service Company, Inc., 1025 Laurel Oak Rd., P.O. Box 1770, Voorhees, NJ 08043.

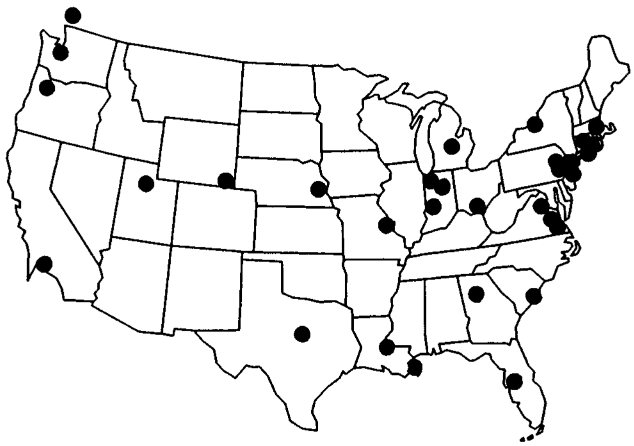

FIG. 1. Map of the study sites.

tion, and a conventional plant with postfilter granular activated carbon (GAC) contactors (Table 2). Preoxidants included ozone, free chlorine, chlorine dioxide, or chloramines, although distribution system residual disinfectants were either free chlorine (17 of 31 systems) or chloramines (14 of 31 systems). Corrosion control within the systems varied between use of phosphate-based corrosion inhibitors (zinc P_i or zinc hexametaphosphate), lime, or pH control to no corrosion control (Table 3). The systems served populations ranging from 13,000 to 3.5 million people and included between 130 and 13,000 mi (1 mi = 1.609 km) of pipe (Table 3). The distribution systems contained between 0 and 100 storage tanks with a total storage capacity ranging between 0 and 13 billion gallons.

Utility data. Routine plant effluent and distribution system operational data were collected from the participating utilities. Data were summarized and reported on a biweekly basis. Reported information included plant production rate in millions of gallons per day, water temperature, turbidity, pH, disinfectant type, disinfectant residual (at the plant effluent, a midpoint in the distribution system, and at a dead-end location), the number of total coliform samples collected and the number of positive samples, the number of total coliform colonies, the number of *Escherichia coli* colonies, the average distribution system plate count level, rainfall, and any changes or disturbances to the treatment process or the distribution system. All analyses were performed by state-certified laboratories by accepted methods. It was requested that all the total coliform enumerations be performed by the membrane filter method with m-Endo media, but occasionally, presence-absence techniques were used.

AOC determinations. Assimilable organic carbon (AOC) levels were determined biweekly by the rapid ATP procedure described by LeChevallier et al. (37). Cultures of *Pseudomonas fluorescens* P17 and *Spirillum* strain NOX were obtained from D. van der Kooij, KIWA, The Netherlands. Cultures were stored in a solution of 20% glycerol and 2% peptone at −70°C.

At each utility, 15 precleaned 45-ml borosilicate glass vials were filled to the shoulder (approximately 40 ml) with plant effluent water, pasteurized at 70°C in a water bath for 30 min, and shipped to the laboratory via overnight delivery. In the laboratory, 12 vials were inoculated with approximately 10^4 CFU of either strain P17 or NOX per ml, final concentration (six vials of each strain). Inoculated vials were incubated at 20°C for 2 to 4 days. One vial was set aside as an uninoculated control. The controls were stored at 4°C to prevent growth of indigenous bacteria surviving pasteurization. Analysis of ATP in the uninoculated control was used to adjust for background levels.

Luminometer measurements were converted into AOC units by determining the level of ATP per cell (either P17 or NOX) and multiplying the value by the standard yield values (4.1×10^6 CFU/μg of acetate C for P17 and 1.2×10^7 CFU/μg of acetate C for NOX) (50, 52, 55).

The remaining two sample vials were used as a growth control and spiked with 100 μg of acetate carbon per ml and 0.1 ml of a mineral salts solution (per liter of high performance liquid chromatography [HPLC]-grade water, 17.1 mg of K_2HPO_4, 76.4 mg of NH_4Cl, and 144 mg of KNO_3). The growth control vials

TABLE 1. Summary of source water characteristics[a]

System code	Source water	Source vulnerability	No. of coliform bacteria/100 ml		Plate count (bacteria/ml)	Turbidity (NTU)
			Total	Fecal		
BC4G8	Reservoir	Fully protected	39	2	2,800	0.59
CA012	Aqueduct	Recreational use; agricultural discharge	80	7	426	1.80
CT107	Reservoir	Limited recreational and agricultural use	4	NR[b]	39	1.02
CT511	Reservoir	Fully protected	19	NR	430	0.53
FL610	River	Recreational use	2,853	662	50	1.86
GA101	Lake	Recreational use	30	6	200	10.00
IN202	River	Recreational use; agricultural, sewage, and industrial discharge	4,200	480	19,000	35.00
IN302	River	Recreational and agricultural use; sewage discharge	22,623	6,501	>10,000	10.00
IN401	Lake	Agricultural, sewage, and industrial discharge	15	0	10	3.00
LA121	River	Agricultural, sewage, and industrial discharge	1,900	420	5,500	91.00
MA845	Lake	Limited public use with recreational and agricultural use	72	51	NR	1.14
MI460	Lake	Limited public use	29	NR	520	2.89
MO631	River	Agricultural, sewage, and industrial discharge	7,400	810	15,000	200.00
NE112	River	Agricultural, sewage, and industrial discharge	1,700	480	13,500	79.00
NJ641	Reservoir	Fully protected	346	NR	2,800	2.60
NJ805	River	Agricultural, sewage, and industrial discharge	4,500	500	NR	10.00
NY466	Lake	Limited public use with recreational and agricultural use	4	2	68	1.40
OH228	River	Recreational use; agricultural, sewage, and industrial discharge	694	125	6,650	47.00
OR204	Reservoir	Fully protected	1	1	61	0.38
PA010	River	Agricultural, sewage, and industrial discharge	11,803	NR	4,829	10.30
PA124	River	Agricultural, sewage, and industrial discharge	130	150	NR	5.51
RI831	Reservoir	Fully protected	39	18	39	0.48
SC406	River	Agricultural, sewage, and industrial discharge	NR	19	NR	4.20
TX101	Lake	Recreational and agricultural use; sewage discharge	4	0	540	3.00
UT116	River	Limited recreational use	15	NR	NR	3.50
VA070	River	Recreational use	540	28	1,514	19.00
VA502	Reservoir	Recreational and agricultural use	201	16	1,372	4.80
VA693	River	Fully protected; recreational use	44	33	662	2.60
VA860	River	Agricultural, sewage, and industrial discharge	400	100	2,000	32.00
WA144	River	Fully protected	38	3	62	0.87
WY009	Reservoir	Recreational and agricultural use	2	NR	15	3.03

[a] Values are annual averages for 1992.
[b] NR, not reported.

TABLE 2. Summary of treatment plant characteristics[a]

System code	Avg water production (mgd)[b]	Treatment process	Preoxidant	Postdisinfectant (mg/liter)	Corrosion control	Plant storage (million gallons)
BC4G8	120.00	Unfiltered surface water	None	Chlorine (0.91)	None	0.0
CA012	420.00	Direct filtration mono-medium	Ozone	Chlorine (1.79)	None	4.0
CT107	62.00	Slow sand filtration	None	Chlorine (0.7)	Lime	15.0
CT511	35.00	Direct filtration dual media	None	Chlorine (2.06)	Zinc hexametaphosphate	3.0
FL610	65.00	Direct filtration dual media	Chlorine	Chloramine (4.07)	None	20.0
GA101	40.00	Conventional dual media	Chlorine/ClO_2	Chlorine (1.82)	Lime and unknown phosphate	6.0
IN202	75.00	Conventional dual media	Chlorine	Chlorine (1.99)	None	25.0
IN302	10.00	Conventional dual media	Chlorine	Chloramine (2.23)	Lime	1.0
IN401	30.00	Conventional dual media	Chlorine	Chloramine (1.23)	Zinc P_i	2.5
LA121	25.00	Direct filtration mono-medium	Chlorine	Chloramine (2.7)	Zinc hexametaphosphate	5.0
MA845	2.90	Conventional dual media (GAC)	Ozone	Chlorine (0.69)	Zinc P_i	0.6
MI460	45.00	Conventional dual media	Chlorine	Chlorine (1.57)	None	10.0
MO631	150.00	Direct filtration mono-medium	Chlorine	Chloramine (2.27)	Lime	15.0
NE112	45.00	Conventional dual media with softening	Chlorine	Chlorine (0.92)	Lime	20.0
NJ641	104.00	Direct filtration dual media	Ozone	Chloramine (3.34)	Sodium hydroxide	1.0
NJ805	120.00	Conventional dual media	Chlorine	Chloramine (0.69)	Lime	2.0
NY466	37.00	Unfiltered surface water	None	Chlorine (2.03)	None	0.0
OH228	105.00	Conventional mono-medium with post-GAC	Chlorine	Chlorine (1.64)	Lime	29.0
OR204	121.00	Unfiltered surface water	Chlorine	Chloramine (1.34)	None	0.0
PA010	32.00	Conventional dual media	Chloramine	Chloramine (2.2)	Zinc hexametaphosphate	3.0
PA124	59.00	Conventional dual media	Chlorine	Chloramine (1.98)	Zinc hexametaphosphate	2.0
RI831	70.00	Conventional mono-medium	Chlorine	Chlorine (0.36)	Lime	0.3
SC406	56.00	Conventional mono-medium (GAC)	Chlorine	Chloramine (3.15)	None	7.5
TX101	15.00	Conventional mono-medium	Ozone	Chloramine (2.99)	Sodium hydroxide	7.0
UT116	22.00	Conventional dual media	Chlorine	Chlorine (0.91)	Lime	0.1
VA070	54.00	Conventional dual media (GAC)	Chlorine	Chloramine (3.71)	Lime	13.5
VA502	71.00	Conventional dual media	Chlorine	Chlorine (2.05)	Zinc P_i	12.0
VA693	49.00	Conventional mono-medium	Chlorine	Chlorine (2.51)	Zinc P_i	NR[c]
VA860	4.00	Conventional dual media	Chlorine	Chloramine (3.13)	Zinc P_i	3.0
WA144	150.00	Unfiltered surface water	None	Chlorine (1.21)	Lime	NR
WY009	14.00	Direct filtration dual media	None	Chlorine (1.09)	None	0.1

[a] Values are based on 1992 data.
[b] mgd, million gallons per day.
[c] NR, not reported.

were used to detect growth inhibitory substances in the water. In addition, a blank vial containing just the mineral salts buffer without added carbon was used to detect carbon contamination of the glassware.

Statistical analysis. All of the data were entered into a relational database (R:Base version 4.5; Microrim, Bellevue, Wash.). Data analysis was accomplished with Lotus 123 version 4.0 (Lotus Development Corporation, Cambridge, Mass.) and Statgraphics plus version 1.0 for Windows (Manugistics, Inc., Rockville, Md.). AOC data were logarithmically transformed prior to analysis. Statistical tests were conducted as though measures over time from each company were independent. It is assumed that the 2-week time periods used in the study were sufficiently long that occurrences during one time period did not necessarily influence the occurrence of a parameter in the next time period.

RESULTS AND DISCUSSION

Coliform bacteria were detected in 27.8% of the 2-week sampling periods. Over 115,000 coliform samples were collected by the 31 systems during the 20-month study. A total of 1,576 samples were positive for coliforms (1.37%), with 35,683 colonies (average, 0.31 CFU/100 ml). The occurrence of coliform bacteria was highest during the months of July to November 1992 and April to November 1993 (Fig. 2). The months of December to March accounted for the lowest rate of coliform occurrence. The mean values for coliform occurrence (both CFU per 100 ml and the percent samples that were coliform positive) were not significantly different (*P* ranging between 0.88 and 0.32) for June through November of 1992 and 1993.

Filtration. Four systems in the study (BC4G8, NY466, OR204, and WA144) used unfiltered surface water. These systems accounted for 28.7% of the total number of coliform samples collected but 64.2% (1,012 of 1,576 samples) of the positive coliform samples. Overall, coliform occurrence averaged 3.1% in the four systems. Three of the four systems reported finding no *E. coli*, suggesting that treatment was not inadequate (i.e., coliforms not related to breakthrough of treatment barriers). One system (NY466) recovered *E. coli* in seven samples in three different 2-week sampling periods. The presence of the *E. coli* bacterium was associated with some of the highest occurrences of coliforms in the system, suggesting the possibility that a cross-connection or breakdown of the disinfection barrier had occurred. However, other episodes of coliform occurrence within the system were not associated with the detection of *E. coli.*

One of the systems (BC4G8) is a large regional wholesaler of water, and it was difficult for the utility to maintain free-chlorine residuals in all parts of the system. Free-chlorine residuals after a 10-min contact time averaged 0.9 mg/liter but declined to an average of 0.25 mg/liter at the midpoint of the system (range, 0.16 to 0.38 mg/liter) and 0.02 mg/liter in dead-end locations (range, 0 to 0.09 mg/liter). The occurrence of coliform bacteria, therefore, in this system could be related to an inability to maintain an effective disinfectant residual in all parts of the system. When the average free-chlorine residual at the dead-end sites was >0.03 mg/liter, the occurrence of coliform bacteria was reduced to 0.36% (2 of 557 samples).

Similarly, site WA144 applied an average free-chlorine residual of 1.2 mg/liter at the point of entry to the system and maintained residuals of 0.8 mg/liter at midpoints in the distribution system. WA144 experienced low chlorine levels in dead-end lines (average, 0.16 mg/liter; range, 0 to 0.6 mg/liter) and experienced increased coliform occurrence (2.5% of 10,745 samples) when dead-end chlorine residuals were less than 0.1 mg/liter. When residuals of 0.2 mg of free chlorine per liter or higher were maintained at the dead-end sites, coliform occur-

TABLE 3. Distribution system characteristics

System code	Population served (10^6)	Amt of pipe (mi)	% Unlined cast iron pipe	No. of open tanks	No. of covered tanks	Total storage capacity (million gallons)	Total AOC (μg/liter)	% Coliform positive	Coliform count (CFU/100 ml)
BC4G8	0.750	900	25	0	10	70	74	11.37	1.201
CA012	3.500	7,000	25	10	90	13,000	142	1.64	1.942
CT107	0.390	1,400	25	0	16	45	69	0.87	0.090
CT511	0.250	926	25	0	14	30.4	120	1.65	0.018
FL610	0.475	2,000	0	0	4	30	99	0.03	0.000
GA101	0.500	400	0	0	10	56	189	0.69	0.024
IN202	0.550	2,000	50	0	4	40	132	0.80	0.025
IN302	0.090	475	15	0	2	3	106	0.62	0.027
IN401	0.250	718	0	0	13	16	42	0.00	0.000
LA121	0.180	572	20	0	8	8	52	0.55	0.012
MA845	0.019	129	16	0	5	11	69	0.41	0.028
MI460	0.270	985	25	0	15	86	72	0.98	0.120
MO631	0.400	1,350	75	0	2	206	33	0.00	0.000
NE112	0.450	2,000	10	0	4	120	70	0.21	0.008
NJ641	0.800	2,000	50	1	12	119	166	0.76	0.000
NJ805	0.500	2,650	40	0	45	75	73	0.51	0.023
NY466	0.240	589	62	3	0	246	115	2.43	0.864
OH228	0.763	2,682	41	0	16	149	50	0.11	0.001
OR204	0.700	1,848	46	5	67	295	50	0.82	0.257
PA010	0.231	1,004	18	0	9	25	74	0.81	0.064
PA124	0.282	530	60	0	0	0	65	0.25	0.012
RI831	0.350	900	30	0	4	125	18	0.21	0.005
SC406	0.400	1,168	0	0	9	25	68	0.37	0.004
TX101	0.500	2,000	0	0	3	7	105	0.38	0.004
UT116	0.200	12,849	61	0	31	242	59	1.55	0.102
VA070	1.000	2,600	1	0	13	33	101	1.30	0.080
VA502	0.600	750	5	0	4	24	170	0.18	0.005
VA693	0.345	1,557	20	0	14	33	156	0.36	0.012
VA860	0.028	161	10	0	2	4.5	76	2.12	0.542
WA144	1.200	1,900	86	9	19	458	64	2.05	0.205
WY009	0.065	350	37	0	3	21	93	0.00	0.000

rence rates were reduced more than 50% (1.2% of 6,175 samples).

OR204, however, was the only unfiltered system that applied a 1.3-mg/liter monochloramine residual (after primary disinfection with free chlorine) and maintained residuals of 0.9 mg/liter at midpoints in the distribution system. The use of a chloramine residual allowed OR204 to usually maintain residuals greater than 0.2 mg/liter in all parts of the system. Coliform levels in the OR204 system were the lowest of the four unfiltered systems.

Peak turbidity levels in the unfiltered systems tended to be higher on average (54 of 148 determinations were >0.5 nephelometric turbidity unit [NTU]) than those in the filtered water systems studied (27 of 892 values were >0.5 NTU). Although the unfiltered systems generally used water with low AOC levels (averaging between 50 and 115 μg/liter), the accumulation of slowly degrading organic material may provide an additional source of nutrients for bacterial regrowth. Three of the four unfiltered-system utilities flushed an average of only 13% of the distribution system each year (no data were available from the fourth system). In addition, turbidity deposits within the distribution system pipelines could accelerate chlorine residual depletion and provide a habitat for bacterial growth. Seidler and Evans (45) reported that routine flushing of an unfiltered water system reduced the occurrence of coliform bacteria.

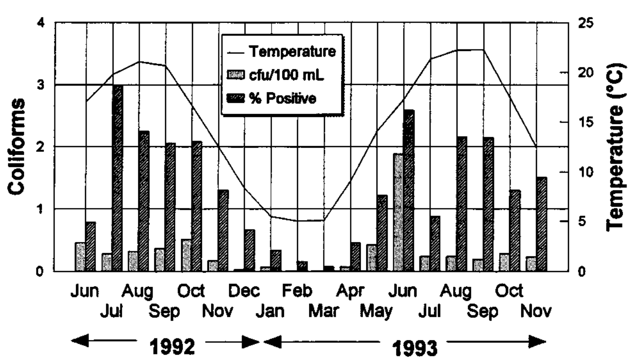

FIG. 2. Relationship between monthly average water temperature and coliform occurrence.

Common characteristics of the unfiltered systems were (i) a lack of control over water chemistry and quality and (ii) complicated distribution systems with many storage tanks (Table 3). Determining the ratio of the number of miles of pipe in the distribution system to the number of storage tanks serving the system was used to compare the relative numbers of storage tanks in a system. A ratio of 100 or less indicates that there are proportionally many storage tanks to the amount of pipe in the system. By this calculation, three of the four unfiltered systems were classified as having a high ratio of storage tanks in proportion to the size of their system. Additionally, there were only five systems in the study of 31 water utilities that had open finished reservoirs. Three of these five open reservoir systems belonged to unfiltered utilities. The many storage tanks and open reservoirs provided opportunities for disinfection residuals to dissipate, AOC to increase as a result of algal growths and redisinfection, contamination, and bacterial growth in sed-

TABLE 4. Relationship between water temperature and coliform occurrence for filtered systems

System type and temp range (°C)	N^a	No. of coliform samples collected	No. of coliform samples positive	% Coliform positive
Free-chlorinated				
0–5	48	3,438	4	0.116
5–10	92	7,485	68	0.908
10–15	108	8,727	48	0.550
15–20	97	9,772	146	1.494
>20	107	7,342	154	2.100
Chloraminated				
0–5	30	1,416	9	0.635
5–10	55	4,561	7	0.153
10–15	58	3,776	15	0.397
15–20	62	5,458	12	0.220
20–25	96	8,244	63	0.764
>25	73	5,793	34	0.587

[a] *N*, number of 2-week intervals analyzed.

iments. The large percentage of unlined cast iron pipe in the system (the overall average for the 31 systems was 28%), the lack of corrosion control, and the lack of a system-wide annual flushing program may have also contributed to the occurrence of coliform bacteria in these systems.

A direct filter plant went on-line at site NY466 in August 1993. Comparison of the coliform occurrence rates from August 1993 to November 1994 with the data for May 1992 to August 1993 demonstrates the benefits of filtration. Prior to filtration, 118 of 3,850 samples were coliform positive, while after filtration, 39 of 3,540 were similarly positive (a threefold reduction). Although some systems practicing filtration also experienced elevated levels of coliforms, the highest level of coliform occurrence in the filtered systems was lower than that in all of the free chlorinated unfiltered systems. These data indicate that filtration is an important factor in preventing coliform regrowth.

Temperature. Temperature is perhaps the most important controlling influence on microbial growth in drinking water, affecting directly or indirectly a wide array of chemical and physical parameters; namely, temperature influences, treatment plant efficiency, microbial growth rate, disinfection efficiency, dissipation of disinfectant residuals, corrosion rates, and distribution system hydraulics and water velocity due to water usage during warm temperature seasons. The problem is, from a practical view, there is little that most water utilities can do to change water temperature.

Most investigators have observed significant microbial activity in water of 15°C or higher (12, 13, 20, 48). Fransolet et al. (20) found that water temperature influenced the microbial growth rate, the lag phase, and the cell yield. For *Pseudomonas putida*, the lag in the growth phase was on the order of 3 days at 7.5°C but only 10 h at 17.5°C. *E. coli* and other enteric bacteria are known as mesophiles, with a growth range of 5 to 45°C. The researchers showed that growth of *E. coli* and *Enterobacter aerogenes* was very slow (growth rates, <0.1 divisions per h) below 20°C (20).

Figure 2 illustrates the relationship between coliform occurrence and average water temperature for the 31 systems studied. Both the frequency of occurrence and the density of coliform bacteria were higher when water temperatures exceeded 15°C. Table 4 further examines the relationship between increasing water temperature and increased occurrence of coliform bacteria for filtered systems using free chlorine and chloramines.

The results show an 18-fold increase in coliform occurrence for free-chlorinated systems when water temperature changed from 0 to 5°C to >20°C. There was a statistically significant difference between the occurrence of coliform bacteria in water of <15°C and that in water of >15°C (Wilcox nonparametric test; $P < 0.0001$). The relationship between temperature and coliform bacteria for chloraminated water was similar to that for free chlorine; however, the magnitude of the increase was much less (2.5-fold increase between <20°C and >20°C) (Table 4).

Systems with warmer water temperatures typically used chloramines to control microbial growth and limit the formation of disinfection by-products. Nearly 75% of the samples collected from chloraminated systems had average water temperatures of >15°C, whereas only 48% of the samples from free-chlorinated systems had average temperatures of >15°C. Considering the tendency towards higher microbial activity at warmer water temperatures, the effectiveness of chloramines is illustrated by the low level of coliforms (relative to the free chlorinated systems) (Table 4) at high temperatures in chloraminated systems.

It should be emphasized that the generalization between water temperature and microbial activity can vary somewhat between systems. Utilities in cold climates may experience increased microbial activity even at cold water temperatures (e.g., <10°C), because the microbial populations present in the supply have adapted to growth at low temperatures. For example, the data for the unfiltered systems, all located in northern climates with an average water temperature of 10.6°C, showed increased microbial activity starting at 5°C and the highest coliform level at temperatures between 10 to 15°C.

Disinfectant residual. Maintenance of a disinfectant residual throughout the distribution system is intended to produce conditions unfavorable for bacterial survival in drinking water. However, in some cases, improper application of a disinfectant can actually enhance bacterial growth conditions. Ozone, for example, can increase AOC levels and unless coupled with biological filtration can result in increased microbial growth in the distribution system (24). There are numerous examples where maintenance of a disinfectant residual did not prevent the occurrence of coliform bacteria in distribution system samples (28, 42). Recent research has indicated that various disinfectants differ in their ability to interact with biofilm bacteria (5, 10, 31–34). Monochloramine, although a more slowly acting disinfectant than free chlorine, is more specific in the type of compounds it will react with and can be more effective in penetrating and inactivating certain biofilms, particularly those containing corrosion products (21, 34).

For filtered systems that used free chlorine, 0.97% of 33,196 samples contained coliform bacteria, while 0.51% of 35,159 samples from chloraminated systems contained coliform bacteria (a statistically significant difference of $P < 0.0001$). The average density of coliform bacteria was 35 times higher in free-chlorinated systems than in chloraminated water (0.60 CFU/100 ml for free-chlorinated water compared with 0.017 CFU/100 ml for chloraminated water; $P < 0.0001$). Previous studies have also found lower levels of coliform occurrence in systems that used chloramines than in those with free-chlorine residuals (26, 33, 41).

The impact of chloramines for control of bacterial occurrence in drinking water is further illustrated by the two systems that converted from free chlorine to monochloramine during the study. Coliform levels at site IN302 decreased 50% following conversion of the system from free chlorine to chloramines. Site VA860 had sporadic occurrences of coliform bacteria enumerated by m-Endo LES from 1990 to 1993 (Fig. 3). Increased

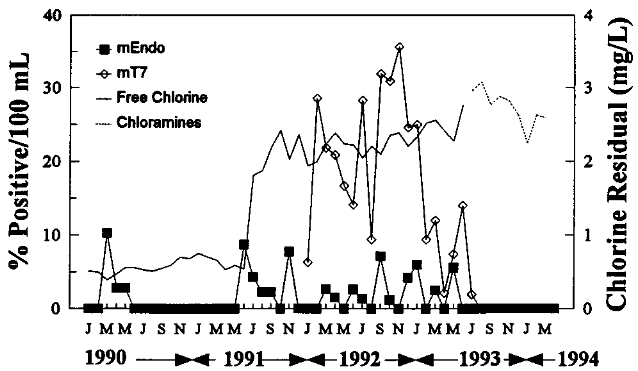

FIG. 3. Average monthly coliform occurrence detected by m-Endo LES and m-T7 media at site VA860.

free-chlorine residuals (between 2 and 3 mg/liter) in response to an episode of coliform bacteria in March 1990 apparently resolved the problem. However, coliforms reappeared in June 1991 and again in November. Although no coliform bacteria were detected in December 1991 or January through February 1992, monitoring of the system with m-T7 agar found coliform bacteria in 10 to 30% of the samples. In nearly 50% of the months during 1992 and the first half of 1993, coliforms were not detected by using m-Endo LES agar (approximately 60 distribution system samples were collected each month), while injured coliform bacteria were routinely found by using m-T7 agar. The value of using m-T7 medium for determining the source of coliform bacteria and the effectiveness of remediation procedures has been documented previously (35, 40).

VA860 converted the distribution system disinfectant to monochloramine (2 to 2.5 mg of residual per liter) during the first week of July 1993. No coliform bacteria have been detected in the distribution system with either m-T7 or m-Endo LES for the 30 months (to the date of this report) following the conversion to chloramines. The dramatic decrease in coliform levels measured by m-Endo LES and m-T7 agar (supplemented with 0.1% sodium sulfite for chloraminated water [54]) provides a strong indication that chloramines were successful for controlling coliform occurrences.

Some of the difference between the levels of coliform bacteria in free-chlorinated versus chloraminated systems can be attributed to the difference in disinfectant levels. The average plant effluent residual for all of the filtered, chloraminated systems was 2.5 mg/liter, whereas the average plant effluent residual for the filtered, free-chlorinated systems was 1.63 mg/liter. Nearly 86% (31,477 of 36,627) of the samples from the midpoint of free-chlorinated systems were less than 1.0 mg/liter despite the fact that plant effluent residuals from 74% of the systems were greater than 1.0 mg/liter. Chloraminated systems had higher midpoint disinfectant residuals (53% greater than 1.0 mg/liter) and higher plant effluent residuals (72% were greater than 2.0 mg/liter) than free-chlorinated systems. Kirmeyer et al. (26) reported that, on the basis of a telephone survey of 30 systems using chloramines, the average plant effluent residual was 2.5 mg/liter (range, 0.6 to 5.0 mg/liter). Nearly three-quarters of the 99 systems listed in the Water Industry Data Base that used chloramines applied doses to achieve residuals between 1.0 and 3.0 mg of total chlorine per liter (26).

The Surface Water Treatment Rule (17) requires maintenance of a disinfectant residual in 95% of the samples collected from the distribution system, while the Total Coliform Rule (18) defines maintenance of a disinfectant residual as a Best Available Technology. The data presented in Table 5 show a U-shaped relationship between disinfectant residual and coliform occurrence. At disinfectant residuals of <0.2 and >1.0 mg of free chlorine per liter, the rate of coliform occurrence and the average bacterial density increased in distributed water.

A similar U-shaped relationship between coliform occurrence and maintenance of a chloramine residual is shown in Table 5. Comparison of the free-chlorine data and the chloramine data illustrates the dramatic difference in the density of coliform bacteria. The worst-case chloramine condition (0 to 0.5 mg of residual per liter) had coliform densities more than five times lower than those of the best-case free-chlorine condition (0.5 to 1.0 mg/liter).

The American Water Works Association (3) recommends a minimum residual goal of 0.5 mg/liter for free chlorine and 2.0 mg/liter for chloramines. The results of this study show that the lowest level of coliform bacteria was achieved by maintaining 0.5 mg of free chlorine per liter or 1.0 mg of chloramines per liter in all parts of the distribution system. Maintenance of a disinfectant residual, however, did not ensure that the occurrence of coliform bacteria can be eliminated (33, 42). The data in Table 5 illustrate that coliform bacteria can still occur in systems that maintain high disinfectant levels.

AOC level. Systems with persistent coliform problems maintained high disinfectant levels in an effort to limit bacterial occurrence. The data shown in Fig. 4 indicate that these systems tended to have some of the highest AOC levels. The geometric mean of AOC levels in systems that maintained free-chlorine residuals of >1.0 mg/liter at dead-end sites was

TABLE 5. Relationship between occurrence of coliform bacteria in filtered distribution systems and maintenance of a disinfectant residual at dead-end sites

System type and free-chlorine residual (mg/liter)	N[a]	No. of samples collected	No. of positive samples	No. of colonies	% of samples coliform positive	Avg no. of coliforms/100ml
Free-chlorinated						
0–0.2	99	11,056	138	10,535	1.248	0.953
0.2–0.5	159	10,637	36	2,850	0.338	0.267
0.5–1.0	164	14,276	87	2,107	0.609	0.147
>1.0	127	7,803	118	4,955	1.512	0.635
Chloraminated						
0–0.5	110	11,447	67	331	0.585	0.029
0.5–1.0	125	7,106	20	66	0.281	0.009
1.0–2.0	121	7,564	13	15	0.171	0.001
>2.0	105	9,835	83	213	0.844	0.022

[a] N, number of 2-week sampling periods analyzed.

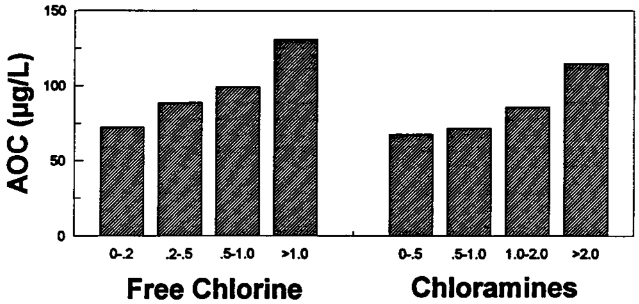

FIG. 4. Geometric mean of AOC levels for waters containing various disinfectant levels.

TABLE 6. Relationship between AOC and the occurrence of coliform bacteria in filtered systems

System[a]	AOC level (µg/liter)	% Samples positive	Avg no. of coliforms/100 ml
Free-chlorinated (N = 11)[b]	120–189	1.24	1.077
	50–93	0.68	0.058
Chloraminated (N = 11)	101–166	0.87	0.022[c]
	42–99	0.36	0.015

[a] N, number of systems.
[b] There were no free-chlorinated systems that had AOC levels that averaged between 94 and 119 µg/liter.
[c] One system reported coliform data in the presence-absence format, and these data were not available to calculate a coliform density.

131 µg/liter, whereas systems that maintained low free-chlorine residuals (0 to 0.2 mg/liter) had AOC levels of 72 µg/liter. Systems that maintained high chloramine levels (>2.0 mg/liter) at dead-end sites had AOC levels of 114 µg/liter, while systems that used low levels of chloramines tended to have lower AOC levels (geometric mean of 67 µg/liter). The average AOC level in highly chloraminated samples (e.g., >2.0 mg/liter) that were coliform positive was 143 µg/liter.

The U-shaped relationship between disinfectant residual and coliform levels observed in Table 5 can be explained because more than one variable was affecting coliform occurrence. Figure 5 illustrates a hypothetical relationship between factors that affect coliform occurrence. At low disinfectant levels, the incidence of coliform detection increases. Alternatively, bacterial levels increase at high nutrient levels. The U-shaped arms describing coliform occurrences can be explained by low disinfectant residuals for the left half of the relationship and increased AOC levels for the right half. Data from Fig. 4 show that systems with high AOC levels needed to maintain high disinfectant levels to attain adequate bacteriological quality, but this approach did not completely control coliform occurrences. Additionally, the relationship suggests that if the systems could reduce AOC levels, lower disinfectant residuals would be needed to maintain bacteriological quality.

Because coliform bacteria are generally considered to be more copiotrophic (e.g., requiring higher nutrient levels), it is expected that higher nutrient levels will be required to initiate coliform regrowth as compared with growth of heterotrophic plate count (HPC) bacteria (35, 50). Although some data showing that low nutrient levels limit bacterial occurrence in individual systems are available (30, 36, 46, 50, 53), there has

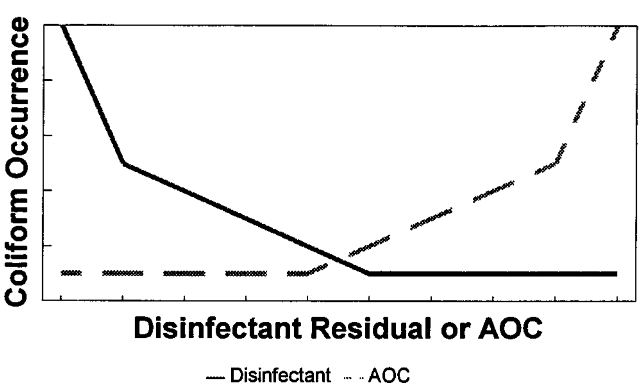

FIG. 5. Hypothetical relationship between coliform occurrence and disinfectant residual and AOC levels.

been no large-scale study to determine how universal these guidelines are for nutrient limitation.

Data to support the relationship between AOC and increased coliform detection are presented in Table 6 and indicate a trend towards increased occurrence of coliform bacteria in free-chlorinated systems that had AOC levels greater than 100 µg/liter. On average, free-chlorinated systems with AOC levels greater than 120 µg/liter had 82% more coliform-positive samples, and the bacterial levels were 19 times higher, than free-chlorinated systems with average AOC levels less than 93 µg/liter (P = 0.024).

By comparison, chloraminated systems had lower coliform densities than free-chlorinated systems regardless of the value for the AOC level. Although the rate of coliform occurrence in chloraminated systems with high AOC levels was 2.4 times greater than for systems with low AOC levels, this difference was not statistically significant (P = 0.11).

Previous research by LeChevallier et al. (30, 36) demonstrated a relationship between AOC levels and the occurrence of coliform bacteria in the free-chlorinated distribution system served by the Swimming River treatment plant of the New Jersey American Water Company. The researchers showed that when AOC levels averaged <100 µg/liter, coliform levels were very low (<0.02 CFU/100 ml). However, when AOC levels were >180 µg/liter, coliform bacterial levels averaged 0.3 to 0.4 CFU/100 ml. The peak occurrence of coliform bacteria (7.5% of the samples contained coliform bacteria) coincided with average AOC levels of 250 µg/liter in the treatment plant effluent (30). The observation that coliform occurrence was <1% when AOC levels were <100 µg/liter in the Swimming River treatment plant is consistent with data from this study (Table 6). Limited data (n = 8) from the South Central Regional Water Authority (New Haven, Conn.) collected in June 1986 showed AOC levels ranging between 220 and 380 µg/liter (7). That same year the South Central Regional Water Authority recovered coliforms in approximately 5% of its samples, with levels averaging 0.25 CFU/100 ml (48).

It is of interest to determine a particular nutrient level at which the growth of coliform bacteria could be limited. However, there are many factors governing the occurrence of coliform bacteria in drinking water supplies, and nutrient levels are only one of these factors. There were only three systems (MO631, IN401, and WY009) that had no occurrences of coliform bacteria during the study. MO631 had high pH levels which inhibited the average AOC to 33 µg/liter. IN401 had an average AOC level of 42 µg/liter, and WY009 had an average AOC level of 93 µg/liter. Conversely, BC4G8, which had an average AOC level of 74 µg/liter, had the highest rate of coliform occurrence (11.7%) of all the systems examined. Therefore, low nutrient levels alone did not ensure indicator-free water.

For filtered systems that maintained an effective disinfectant residual throughout the distribution system (at least 0.5 mg/liter for free chlorine and 1.0 mg/liter for chloramines), low AOC levels can probably limit the regrowth of coliform bacteria. For systems that are experiencing bacterial regrowth problems, one option would be to lower AOC levels to less than 100 μg/liter (30). Because groundwater systems rarely experience coliform regrowth problems, a second option would be to lower the AOC of surface water supplies to levels similar to those of groundwater, about 50 μg/liter (4, 11, 25). A third option would be to reduce AOC to <10 μg/liter, a level recommended by van der Kooij (50) to limit growth of HPC bacteria in unchlorinated systems. The first two options are readily achievable by use of conventional single- or dual-stage filtration, but the third option would be very difficult (and perhaps unnecessary because U.S. utilities are required to maintain a disinfectant residual in distributed water) to achieve by conventional treatment (22).

Corrosion control. Corrosion of iron pipe surfaces can produce tubercles which increase the surface area of the pipe, increase the hydraulic mixing and transport of nutrients to the surface, precipitate organic compounds, and provide cracks and crevices which protect bacteria from disinfection. Disinfection of biofilm bacteria on galvanized copper or polyvinyl chloride pipes was effective when 1 mg of free chlorine or monochloramine per liter was used, but disinfection of organisms on iron pipes was ineffective even when organisms were exposed to 5 mg of free chlorine per liter for several weeks (28). A combination of the corrosion rate, the molar ratio of chloride plus sulfate to bicarbonate (the Larson index), the chloramine residual, and the level of corrosion inhibitor accounted for 75% of the variation in biofilm disinfection rates for microorganisms grown on iron pipes (34).

The occurrence of coliform bacteria in corrosion tubercles on iron pipes has been reported by a number of investigators (6, 14, 15, 29, 43). Emde et al. (14) reported isolating coliform species, including *E. coli*, *Enterobacter aerogenes*, and *Klebsiella* spp., from iron tubercles in the Yellowknife, Northwest Territories, Canada, distribution system. Water treatment consisted of chlorination (1.0 mg of free chlorine residual per liter), fluoridation (hydrofluosilicic acid), and, in the winter, heat (to 4°C). A companion study showed that corrosion tubercles contained greater numbers of coliform bacteria than did the untreated or chlorinated water (15). Lowther and Moser (38) reported that levels of coliform bacteria decreased within a few weeks following the application of zinc P_i in the Seymour, Ind., distribution system. The addition of lime (39) or an increased distribution system pH (23) has also been reported to help control coliform problems. In both of these situations, reduced corrosivity of the water could have resulted in improved disinfection of biofilm organisms.

Most of the systems surveyed did not routinely collect corrosion data on treated water; however, monthly data were available from a few sites. Site IN302 had corrosion rates ranging from 0.7 to 2.6 mils per year (1 mil = 0.001 in. [1 in. = 2.54 cm]) with levels approximately four times higher in April and May than in November 1993. A similar trend was observed for site VA070, with corrosion rates as high as 10 mils per year during the summer and 2 mils per year during the winter. However, because both systems maintained chloramine residuals, the impact of the elevated corrosion rates on coliform occurrence was not apparent (34). Site NY466 (an unfiltered system that maintained a free chlorine residual) experienced increased coliform occurrence when corrosion rates rapidly increased from 0.7 to 2.5 mils per year in May 1994.

The relationship between the number of miles of unlined cast iron pipe and coliform occurrences also suggests that corrosion of iron pipe surfaces is an important factor affecting coliform occurrences. When the size of filtered, free-chlorinated distribution systems was analyzed, there was no substantial difference in coliform occurrence rates between large and small systems (0.79% coliform occurrence rate for systems with >1,000 mi of pipe compared with 0.61% coliform occurrence rate for systems with <1,000 mi of pipe). However, when the miles of unlined cast iron pipe were calculated, filtered free-chlorinated systems that had more than 1,000 mi of unlined cast iron pipe had, on average, three-times-higher coliform levels (1.025% positive; $n = 4$) than systems with 0 to 200 mi of unlined cast iron pipe (0.32% positive; $n = 4$). The presence of unlined cast iron pipe in chloraminated systems had no discernible impact. A recent assessment of North American water distribution systems reported an average of 22.2% of distribution system pipelines were composed of unlined cast iron pipe (27). For the 31 systems examined in this study, the average distribution system contained 28% cast iron pipes. However, seven utilities (IN202, NJ641, PA124, UT116, NY466, MO631, and WA144) contained 50% or more unlined cast iron pipe within the distribution system.

Approximately one-third of the utilities examined used pH or lime addition to control corrosion, one-third used a phosphate-based inhibitor (either P_i or polyphosphate), and one-third practiced no corrosion control. The use of phosphate-based corrosion inhibitors was found to be associated with lower coliform levels. On average, coliform levels were 36% lower in free-chlorinated systems that reported phosphate levels greater than 0.1 mg/liter than in systems with lower phosphate levels.

Better data linking bacterial growth in the distribution system and corrosion control are needed. The limited corrosion data available from utilities in this study illustrate that most systems do not measure corrosion rates daily.

Engineering and operational factors. A number of operational characteristics of the treatment process or the distribution system were also associated with increased rates of coliform occurrence.

(i) Large proportion of storage tanks. Storage tanks within the distribution system are necessary to provide adequate pressure, fire protection, and water reserves. However, storage tanks can be locations where water stagnates, disinfectant residuals dissipate, and microbial water quality deteriorates. Among the 31 utilities examined, the number of storage tanks or reservoirs within the distribution system ranged from 2 to 100. To evaluate the impact of the number of storage tanks within a system, a ratio of the miles of distribution pipe to the number of storage tanks was determined.

For filtered free-chlorinated systems, the analysis showed that only one of six systems with high coliform detection frequencies (greater than 0.5%) had greater than 100 mi of pipe per storage tank (overall geometric mean for the six systems, 90 mi per tank), whereas six of seven systems with coliform detection frequencies of less than 0.5% had greater than 100 mi of pipe per storage tank (overall geometric mean for the seven systems, 142 mi per tank). Filtered, chloraminated utilities showed a similar trend, with systems having low coliform occurrence rates (less than 0.5%) having proportionally few storage tanks (geometric mean, 276 mi per tank) and systems with higher occurrence rates (>0.5%) having more storage tanks per mile of pipe (geometric mean, 107 mi per tank).

The total capacity of storage within the system was not related to coliform occurrences. Filtered, free-chlorinated systems with low coliform levels had an average storage capacity of 46 million gallons, while systems with higher coliform rates had an average storage capacity of 48 million gallons (excluding CA012, which had storage of 1,300 million gallons; including CA012, the geometric mean of storage capacity increased to 123 million gallons). Filtered, chloraminated systems with low coliform occurrences had an average storage capacity of 28 million gallons, while systems with higher coliform levels had an average storage capacity of 37 million gallons.

(ii) Uncovered finished water reservoirs. Not only do uncovered finished water reservoirs provide an opportunity for fecal contamination of potable water supplies from birds and other animals, but algal blooms can also increase AOC levels. Multiple points of rechlorination may be a mechanism to increase AOC following storage of water in open reservoirs. In a limited study (five replicate samples) of AOC levels following rechlorination of three open reservoirs, a small (15%) but persistent increase in AOC levels was observed (28a). In this study, all five systems (three of them were unfiltered) with open finished reservoirs had coliform occurrence rates of >0.75%. However, CA012 is a filtered, free-chlorinated system with 10 open finished reservoirs and had one of the highest coliform occurrence rates (1.64% of the samples positive; average coliform level, 1.94 CFU/100 ml) in its category. NJ641 is a filtered, chloraminated system with one open finished reservoir, and it had a coliform occurrence rate of 0.76%.

(iii) Distribution system flushing. Annual flushing of the distribution system to remove accumulated sediment is considered a basic maintenance procedure (2). Sediments can also provide shelter for microorganisms in drinking water systems. Sediment from a system experiencing coliform regrowth episodes was shown to contain high levels of HPC bacteria ($>8 \times 10^6$ CFU/g) and coliform organisms (29). The sediment in this system was also covered by a layer of postprecipitation from improperly applied treatment chemicals. The control of sediment accumulation in distribution system pipelines by routine and aggressive flushing is important because even recalcitrant organic compounds can be slowly biodegraded in the sediments and provide an endogenous supply of nutrients. In this study, the majority (four of seven) of free-chlorinated systems that had low occurrence rates of coliform bacteria (<0.5% of the samples were coliform positive) flushed 100% of the distribution system on an annual basis, while only one of six systems with high coliform occurrence rates (>0.5%) performed a similar cleaning program.

(iv) Source water protection. There is little information on raw sources of AOC or impacts of watershed control on limiting soluble nutrients in drinking water. As a result, there are few clues as to why a particular source water may be high in AOC or how to control it. In this study, AOC levels were measured in plant effluent samples, so it is difficult to determine how the variety of treatment processes employed may have increased or decreased nutrient levels. In general, raw water total coliform, fecal coliform, and HPC bacterial levels (Table 1) were higher in systems with high plant effluent AOC levels (>100 μg/liter) than in systems with low AOC levels (<100 μg/liter), but this difference was not statistically significant. Examination of water-soluble extracts from domestic sewage sludge has shown AOC levels of 5 g/liter (40a). In this study, utilities were asked to rate the level of source water protection with respect to upstream sewage or agricultural activities. Qualitative determination of watershed protection did not correspond to either the raw water bacterial level (total, fecal, or HPC bacteria) or the plant effluent AOC level. Clearly, additional research is necessary to evaluate raw water AOC sources and control.

(v) Ozone without biological treatment. Four of the 31 systems studied used ozone as a disinfectant within the treatment process. The increase in biodegradable material caused by ozone has been observed by many investigators (9, 16, 44). A combination of ozone followed by GAC filtration can produce reductions in AOC levels due to microbial activity within the carbon bed. In this study, three of the systems that used conventional treatment following ozonation had an average plant effluent AOC level of 138 μg/liter (range, 105 to 166 μg/liter), while the system that used ozone and GAC had an average AOC level of 69 μg/liter.

TABLE 7. Relationship between rainfall events and occurrence of coliform bacteria in distribution system samples

System type and amt of rainfall (in.)[a]	N[b]	No. of samples collected	No. of positive samples	% Samples coliform positive
Free-chlorinated				
0–0.5	146	14,659	240	1.637
0.5–1	92	5,741	24	0.418
1–2	122	7,433	37	0.498
2–3	83	5,589	31	0.555
>3	67	5,375	31	0.577
Chloraminated				
0–1	153	11,027	47	0.426
1–2	127	9,972	51	0.511
2–3	84	7,320	50	0.683
>3	46	4,950	35	0.707
Unfiltered				
0–2	101	22,942	699	3.093
>2.0	50	11,332	295	2.603

[a] 1 in. = 2.54 cm.
[b] N, number of 2-week sampling periods analyzed.

(vi) GAC or slow sand filtration. Slow sand filtration, and even conventional prechlorinated GAC filters, can provide a significant level of microbial activity that can result in decreases in treated AOC levels (30). In this study, 5 of the 12 systems with AOC levels less than 90 μg/liter used either GAC or slow sand filters, whereas only 1 of the 12 systems with AOC levels greater than 90 μg/liter used either GAC or slow sand filters (excluding unfiltered utilities and systems with high pH). Future research should evaluate mechanisms to optimize conventional treatment for maximal AOC removal.

Rainfall. Previous studies have associated the occurrence of coliform bacteria in drinking water systems with rainfall events (28, 49, 55). However, rainfall is a complex variable and may have many different impacts on drinking water quality. Rainfall can be a mechanism that introduces coliform bacteria into the system through leaks and cross-connections (49, 55). Rainfall can wash dissolved nutrients into the watershed and increase organic carbon levels. Acid rain can depress alkalinity levels and stimulate corrosion. However, in times of drought, the lack of rain can result in proportionally higher levels of dissolved minerals or nutrients in the source water that can stimulate increased corrosion or bacterial growth in the pipe network.

The data presented in Table 7 indicate that coliform occurrence rates increased 66% in chloraminated systems when rainfall levels increased from 0 to greater than 3 in. (over a 2-week interval). A similar pattern was observed for free-chlorinated systems, where coliform occurrence rates increased 38% as rainfall levels increased from 0.5 to >3 in. The exception to this pattern was when no rainfall was observed, but these data were greatly impacted by a single Southern California system (CA012). No discernible relationship between rainfall and coliform occurrences was detected for the four unfiltered systems.

These results indicate a mixed effect for rainfall on coliform occurrences. In general, increased rainfall levels appear to be related to increased coliform occurrence rates. However, in some systems, the absence of rainfall may also stimulate coliform regrowth. Other factors that may be important can include the amount of time between rainfall events, the intensity of precipitation, and the nature of the watershed.

Summary. Although the data from this study showed that there were common characteristics for systems that experienced persistent coliform regrowth problems, the results also indicate that each system was unique in the particular set of variables that were important for that utility. The ability to determine the significant regrowth factors is dependent upon the system developing a good data set of monitoring results. It is recommended that systems with prior histories of bacteriological problems begin to develop such a data set on which to base sound management policies. In addition to the routine data collected by most systems (disinfectant residuals, temperature, and pH, etc.), it is recommended that the following analyses be performed periodically (e.g., once a week or once a month depending on the system size and analytical capabilities): coliform enumeration with m-T7 agar, HPC test with R2A medium, AOC or biodegradable dissolved organic carbon analysis, and corrosion measurements. It would also be useful if utilities evaluated hydraulic models of their distribution systems to determine residence times and disinfectant residuals under different operating scenarios. A system armed with this information can make proactive changes to prevent regrowth problems and focus on critical areas once coliform occurrences begin.

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