Effectiveness of Water Treatment Processes

AS MEASURED BY COLIFORM REDUCTION

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service

EFFECTIVENESS OF WATER TREATMENT PROCESSES

As Measured by Coliform Reduction

Part I
Water Treatment Plant Data

Part II
Special Cooperative MF-MPN Study

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

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Abstract

During 1954–56 the author personally visited more than 80 water treatment plants in the United States which had been reported to have adequate coliform bacteriological data and to treat raw waters with monthly average coliform bacterial densities in excess of those recommended by the Public Health Service. Data from nearly 60 of these plants have been analyzed to determine the effectiveness of various water treatment processes as measured by their reduction of coliform bacteria.

As one of the requirements of the *Public Health Service Drinking Water Standards* is that samples for bacteriological examination must be taken from representative locations throughout the distribution system, these standards are not applicable where only plant effluent samples are examined. Thus it was necessary to assume a bacterial quality objective for plant effluent data. Analysis of the data presented in this report shows that well-operated plants of good design consistently produced plant effluent samples having not more than 2 per cent of all 10-ml portions examined during any one month postive for coliform bacteria. This is the assumed bacterial quality objective for water plant effluents that is used throughout this report.

The limited data available indicate that "clean" waters containing monthly average coliform densities somewhat in excess of 50 per 100 ml can be treated by simple chlorination to produce water conforming to the assumed bacteriological objective for plant effluent. The term "clean" implies that the water must be free from particulate matter in which coliform bacteria are so imbedded as to survive disinfection.

Although disinfection, coagulation, and sedimentation as practiced at some plants did produce water conforming to the assumed bacteriological objective for plant effluent, there is evidence that coliform bacteria imbedded in particulate matter may survive such treatment. Filtration or other means for removing particulate matter should be provided at any plant treating water containing appreciable coliform loading.

Coagulation, sedimentation, and filtration are inadequate treatment for waters containing any appreciable coliform loadings. Continuous and adequate chlorination must be provided.

Adequately designed and well-operated water treatment plants can treat raw waters heavily laden with coliform bacteria to pro-

duce plant effluents conforming to the assumed bacteriological objective. More intensified chlorination has made this possible.

The effectiveness of water treatment processes, particularly chlorination, in removing or inactivating coliform bacteria raises the question of whether the coliform bacterial content by itself is adequate criterion of the biological safety of a potable water. Although laboratory studies indicate the residual chlorine levels required to kill or inactivate certain viruses are higher than those required to destroy coliform bacteria, there are no epidemiological data indicating that viruses survive treatment provided by a modern, well-operated water plant. Additional research is needed before this apparent inconsistency can be reconciled.

While indiscriminate pollution of our water resources cannot be tolerated, it should be recognized that, if necessary, water plants can treat waters heavily laden with coliform bacteria. Important factors in securing effective continuous treatment of such waters are the adequacy of the plant and the abilities of the operating personnel.

I. Water Treatment Plant Data

CURRENT STATUS AND STUDY PROCEDURES

Numerous State and other agencies have established bacterial-quality standards or objectives for waters used as sources for the production of portable water. Many of these have been influenced by the Public Health Service recommendations (1) which may be summarized briefly as follows. For waters acceptable for treatment by simple chlorination, the average coliform bacterial density should not exceed 50 per 100 ml for any month. For waters acceptable for treatment by conventional rapid sand filtration with continuous postchlorination, the monthly average coliform density should not exceed 5,000 per 100 ml, and not more than 20 percent of all samples examined during any month should exceed that coliform density. The use of auxiliary treatment–prechlorination, presedimentation, or equivalent–does not permit an increase in the monthly average coliform density, but does permit more than 20 percent of those samples examined in any one month to exceed 5,000 per 100 ml, provided not more than 5 percent exceed 20,000 per 100 ml.

Previous Studies

These recommendations have been based mainly on the work of Streeter and his associates (2) (3) (4) whose studies involved the collection and analyses of data from 14 plants located along the Ohio River (1923–1924), from 7 plants located in Ohio and the Middle Atlantic States (1923–1924), from 13 plants treating waters from the Great Lakes (1926–1927), and from 5 years operation of an experimental plant at Cincinnati, Ohio (1924–1929).

All data, except those for the experimental plant, were for plants disinfecting water by postchlorination only. The annual average chlorine dosages applied did not exceed 0.3 mg/l at 18 of the 28 plants. Information on the chlorine residuals in the effluents at these plants is lacking.

The only data involving prechlorination were from 14 months operation of the experimental plant. During the first 11 months the prechlorine dosage was regulated to provide approximately 0.05 mg/l total residual chlorine in the water applied to the filter.

This low chlorine residual was maintained to prevent destruction of the biota on the filter. The filter effluent was rechlorinated to provide a total residual chlorine of 0.05 mg/l in the finished water. Higher chlorine concentrations were considered undesirable due to possible development of tastes and odors.

Greater prechlorination dosages were used throughout the last 3 months. Average monthly concentrations of 0.36, 0.76, and 0.33 mg/l were recorded for the water applied to the filter. This increase in chlorine content resulted in considerable destruction and sloughing of the biota on the filter. During the second month the chlorine residual in the water dropped from 0.76 to 0.01 mg/l as it passed through the filter. Throughout this period postchlorination was used to provide between 0.05 and 0.10 mg/l total chlorine residual in the finished water.

In general, the coliform densities of the raw waters at the plants studied were obtained using single-tube plantings in decimal dilutions, presumptive tests, and were expressed in terms of the "Indicated Number" (Phelps's Index).

In 1950, Streeter (5) made a resurvey of the bacterial efficiencies of water treatment plants for the Ohio River Valley Water Sanitation Commission. Data from six plants were analyzed and compared to similar information from these same plants for the period 1923–24. Again raw water coliform densities were determined using single-tube plantings in a decimal dilution series and reported in terms of the "Indicated Number." In all cases, the presumptive test only was used.

In summarizing these data, Streeter (5a) states:

> From the standpoint of tolerance, a limiting average coliform density of 10,000 per 100 ml (I.N.) would be adequately safe, but would involve the continued dependence on intensified chlorination as an integral part of every water purification plant.

However, in consideration of the desire to provide a safe and palatable drinking water, he recommended (5a):

> an ultimate bacterial-quality objective such that the monthly arithmetical average "Most Probably Number" of coliform bacteria in the river at all water supply intakes will not exceed 5,000 per 100 ml in any month; nor will exceed this figure in more than 20 percent of the samples of raw water examined during any month; nor will exceed 20,000 per 100 ml in more than 5 percent of such samples.

In a panel discussion in 1950, Faber (6) presented data for six plants, five of which had average annual coliform densities in raw water ranging from 5,000 to 2,000,000 [1] "Most Probable Number" per 100 ml. All plants used prechlorination. According to the information presented, the coliform densities in the waters applied to the filters at all three plants reporting such data were

[1] 2.3 times an Indicated Number of 890,000.

zero, and those for the finished water at all five plants reporting data were zero. The sixth, a Canadian plant, reported the finished water to be of "safe sanitary quality."

The Public Health Service recommendation regarding the permissible average coliform bacterial density in water acceptable for treatment by simple chlorination has been based on data resulting from postchlorination of filter effluent water. From their studies, Streeter and his associates (4a) concluded that water conforming with the *"Treasury Department B.coli standard"* can be produced by simple chlorination of Ohio River water provided the limiting *B. coli index* (I.N.) does not exceed 80 per 100 ml, and from Great Lakes water, provided this index does not exceed 50 per 100 ml.

Treatment Processes, 1930 vs. 1956

Since 1930, pollution has resulted in increased bacterial loadings of raw waters. Many plants are now treating waters having coliform densities far in excess of the limiting values recommended by the Public Health Service.

Plant design and operation have also changed. Prechlorination, or at least chlorination prior to filtration, is the common practice. Many plants carry substantial chlorine residuals—as high as 1 mg/l free chlorine—in their finished water. Numerous filters have been constructed or rebuilt using coarser sand, and filtration rates of 3 or more gallons per square foot per minute are frequent occurrences during summer periods of peak production at many plants. The problems due to mud balls and caking of sand in filters have been eliminated to a large extent by better backwashing. Improvements in coagulation and sedimentation have reduced turbidities to a point where those in the water applied to the filter are usually less than 5 units, and at most plants the practice of filtration to waste to establish a "schmutzdeck" has been discontinued.

Finally, better plant control has been secured through more adequate laboratory equipment, better trained personnel, and improved laboratory procedures. Probably the most important advancement in the water treatment field in recent years has been the increased use of chlorine which has resulted from the better understanding of the chemical reactions involved and the disinfecting properties of free and combined chlorine.

It is also to be noted that the current *Standard Methods* (7) recognizes only the "Most Probable Number" for reporting the density of coliform organisms, while Streeter used the "Indicated Number (Phelps's Index.) This is significant when one considers that for single-tube plantings in a series of decimal dilutions the ratio of the average monthly "Most Probable Number" to that of the "Indicated Number" is approximately 2.3 to 1.

Plants Studied

Although recognizing the numerous problems involved, it was decided to base this study on data available from operating plants. Through the assistance of State departments of health, a tentative list of plants to be considered was prepared. These were selected on the basis of (a) frequent average monthly raw water coliform bacterial densities in excess of current Public Health Service recommendations, and (b) the adequacy of the bacteriological data available.

Some 80 plants were visited. Monthly summary records showing average daily data, general information on the design and operation of the plant, and data on bacteriological procedures have been obtained from approximately 60 conventional filtration plants, three simple chlorination plants, and one plant treating water by coagulation, sedimentation, and disinfection.

A list of plants, data from which have been used in this study, is shown in table 1. Treatment facilities and average chemical dosages for the period covered at each plant are given in table 2. The data on chemical applications are approximate as they are based on averages of monthly average data from plant records. Also, the purity of the chemicals varied. Further, some chemicals which were used occasionally may not have been included in summary data records available for this study.

Considerable difficulty has been encountered in evaluating the data obtained from different plants. Rather cursory examinations of bacteriological laboratory equipment and procedures for coliform examination of waters at these plants indicate numerous departures from the 1946 edition of *Standard Methods* (8). Probably the most important of these were (a) media of insufficient strength—somewhere between 10 percent and 20 percent of those plants visited used single-strength medium for 10-ml plantings—and (b) failure to transplant 24-hour presumptive positives immediately for confirmation. Other frequently encountered departures were (a) use of media other than lactose or lauryl tryptose broth for initial raw water plantings, (b) prolonged exposure of media to heat in autoclaving, (c) use of distilled water for dilution water (also use of tap water containing chlorine), and (d) unsatisfactory dilution techniques, such as making multiple 10–to–1 dilutions or the use of cotton-stoppered dilution bottles or tubes which make it impossible to agitate the contents properly. Although these data are from a select group of plants

TABLE 1

WATER TREATMENT PLANTS STUDIED

Alton, Ill.
American Sugar Refinery Co.
  New Orleans, La.
Anheuser-Busch, St. Louis, Mo.
Appleton, Wis.
Ashland, Ky.

Batavia, N. Y.
Beaver Falls (Eastvale), Pa.
Beaver Falls (New Brighton), Pa.
Bridgeport, Conn.

Cedar Rapids, Iowa
Celanese Fibers Co., Rome, Ga.
Cincinnati, Ohio
Columbus, Ohio

Dallas (Elm Fork), Tex.
Danville, Va.

East Liverpool, Ohio
East St. Louis, Ill.
E. I. DuPont, Spruance Works, Va.

Fieldcrest Mills, Inc., Spray, N. C.
Flat Rock, Mich.
Flint, Mich.
Frankenmuth, Mich.

Granite City, Ill.

Hackensack Water Co., New Milford, N. J.
Huntington, W. Va.

Indianapolis (Fall Creek), Ind.
Indianapolis (White R.), Ind.

Kansas City, Kans.
Kansas City, Mo.

Laredo, Tex.
Lawrence, Kans.
Lawrence, Mass
Lorain, Ohio
Louisville, Ky.

Minneapolis, (Fridley), Minn.
Moline, Ill.

Nashville, Tenn.
New Albany, Ind.
New Castle, Pa.
Nitro, W. Va.

Omaha, Nebr.
Ottumwa, Iowa

Passaic Valley Water Commission,
  Clifton, N. J.
Port Huron, Mich.
Portsmouth, Ohio
Poughkeepsie, N. Y.
Pueblo, Colo.

Quincy, Ill.

Rome, Ga.

Salisbury, N. C.
Salt Lake City, Utah
St. Louis (Chain of Rocks), Mo.
St. Louis (Howard Bend), Mo.
St. Louis County, (Central Plant), Mo.
Streator, Ill.

Waukegon, Ill.
Weirton, W. Va.
Wyandotte, Mich.

with respect to laboratory control, in some cases they must be considered of questionable value for use in research.

Except for residual chlorine concentrations, which were commonly determined by the orthotolidine procedure and usually reported as total chlorine, plant records were generally adequate.

Analysis of Bacteriological Data

As previously stated there were many variables in the quality and precision of the bacteriological data obtained from different plants. In general, raw water data have been based on at least five daily samples per week, with each sample tested by one or more plantings in each of a series of decimal volumes. Most of the plants examined raw water by the presumptive test, but several used the confirmed test or made the initial planting directly into brilliant green lactose bile broth.

Where possible, MPN values have been taken from tables (9); however, those for a few plants using other than the decimal dilution system were calculated by Thomas's (10) approximate method. Indeterminate results having all portions positive have been assumed to have an MPN equal to or greater than that which would have occurred if the next decimal dilution had been planted and all portions found to be negative. Thus, if all portions of

Table 2.—*Treatment plant facilities and average chemical dosages*

Plant Code number	Type of plant	Treatment facilities and chemicals	Days of record	Water treated, mgd	Aluminum sulfate, mg/l	Ferrous sulfate, mg/l	Ferric sulfate mg/l	Activated silica, mg/l	Sodium aluminate, mg/l	Activated carbon, mg/l	Lime, mg/l	Soda-ash, mg/l	Carbon dioxide, mg/l
1	P	So Ng De Cas Mtb So Frs Sc	730	16.0	[a]38							[a]6	
2	P & H	Ng Dc Cil (MtpsSv) Frs Dc Sc	361	1.4		[a]31					[a]103		
3	P & H	Cl Mb So Ci Dc (MtpsSv) Kc So Frs Sc	730	3.8			[a]24				[a]150		
4	P	Ng Dc Ca Tc Mp So Frs Dc Kp Sc	730	4.4	[a]16					[a]0.5	[a]10		
5	P	Mh Sm Calt Mhp Sm Dc Mtp So Frs Sc Nc Dc	731	28.0	[a]16			[a]0.8			[a]10		
6	P	So Cal Tc Mtp Sm Dc So Frs Sc Dc	730	3.6	[a]14					[a]2.8	[a]22		
7	P & H	Nc Dc Cat Tc As Cl (MtpsSv) Ca Tc Mtp Sc R Frs(a) Nc Dx Sc	730	5.2	[a]26			[a]4.5		[a]4.0	[a]118		(X)
8	P	Dc Cal Mtp Sc Frs Kp As Sc Dc	719	7.0	[a]35						[a]16		
9	P & H	Ng Dc Cal Tc Mtp Smo R Frs Dc Kc Sc	730	4.9	[a]34					[a]5.4	[a]140		
10	P	Tc Ca As So Dc So Frs Kc Dx Sc	730	4.8	[a]72					[a]34.0			
11	P	Dc Cas Mtp Sm Frs Dc Kp Sc	699	1.7	[a]20							[a]24	
12	P & H	Sm Nc Dc Cails Mbp Tc Cai Mp S R Dc Frs Sc	731	75.0	[a]4		[a]2.25			[a]1.2	[a]166	[7]9	(X)
13	P & H	Dc Sm Cals Dc Mtp Sm R Ca So R Frs (a) Sc Nc	731	2.8	[a]16			[7]5.0	[3]6.2		[a]229	[a]12	(X)
14	P	Dc Ca Tc Mb So Kp Frs Dx Sc	730	3.8	[a]17					[a]3.2	[a]9		
15	P & H	Sc So Cails Mb Sm R Tc S R Frs Dc So Dd Fac Kp Ng Dc	624	5.0	[1]28	[a]80				[a]4.6	[a]228	[a]69	[a](X)
16	P	Dc Ca Mtp Scm Dc Frs Nc Sc	731	22.0	[a]16								
17	P	Dc Ca Mtps Sv (MiSo) Dc Frs (Fs) Sc	731	2.8	[a]20						[1]10		
18a	P	Dc Ca Mp Sm Frs Dc } Sb.	681	13.5	[a]24								
18b	P	Nc Dc Ca So Nc Dc So Fr Dc } Sb.	730	27.0	[a]29								
19	P & H	Cals Mb (MtpsSv) R Cas Nc Tc Mb Dc So Frs Ng Dc Sc	730	25.8	[a]42					[a]4.4	113	[1]18	(?)
20	P	Dc Ca Mb Tc Sc Dx Frs Sc	730	4.6	[a]13					[a].4			
21	P	Dc Ca Tc Mb So Kp Frs Dx Sc	730	2.7	[a]16					[a]3.1	[a]7		
22	P	Dc Cas Mip So Frs Ng Dc Sc	730	3.8	[a]18						[a]12	[a]5	
23	P	A Dc Cil (MtpsSv) Dx Frs Dx Sc	730	1.5		[a]48					[a]36		
24	P	So Dc Cal Mb So Tc Dc Ca Mb So Dc Frs Dc So	730	54.0	[a]18					[2].4	[a]12		
25	P	So Cal Dc Mib So Frs Dc Kp Sc	730	3.2	[a]16					[a]2.0	[1]40	[a]34	
26	P	Cal M So Frs Kc Nc Dc (x) Sc	731	5.2	[a]31						[a]10		
27	P & H	Tc Cal Mbp Sm Ci Dc Tc Mtp Sm R Dc Frs Sc	730	9.2	[a]28		[a]5.5			[a]6.7	[a]120	[a]8	
28	P	Dc Ca Mib So Frs As Fs Kp So Dc	730	7.6	[a]33						[a]10		
29	P	Nc Dc Ca Tc Mi So Frs Kp Sc Dx Sc	730	6.7	[a]37					[a]1.6	[a]22	[a]8	
30	P	Dc Ca Tc Mi A Cl So Mp So Frs Sc Dx Sc	730	2.9	[a]20					[a]4.1	[a]31		
31	P	Ca Mp So Cal Dc Mtp Sm Frs Dx Sc	729	4.8	[a]12						[a]11		
32	P & H	So Cail Mb Sm Nc Dc Ca Mb Sm Frs Nc Dc Sc	731	108.0	[a]16	[a]9					[a]92		
33a	P	A Cail Mtp Sm } A Cai Mtp S Mtp Dc Sm Dc Frs Sc Dc											
33b	P	A Cail Mtp Sm } Cal Mtp Dc Sm Dc Frs Sc Dc	730	6.6	[a]60		[a]36				[a]46		
34	P & H	So Cl Mt Cai Mb Sm Cai Mb Cai Nc Dc Sm Dc Frs Sc	731	64.0	[a]12	[a]8					[a]94		
35	P	So Cal M So Frs Sc N Dc(x) Sc	731	28.0	[a]39						[a]14		

36	P & H	Ci So Ne De Ci Mip So Ci Mp So Ci Ne De Frs Sc	731	41.0	....	....	•7	....	....	....	•120	....	•(X)
37	P	Ne De Cat Mop So Frs Kp Sc	730	6.5	•17	....	....	(?)	....	•1	....	•10	....
38	P & H	De Cat Mb So Cl Mt Sm R Dd Ne De So Frs Sc	629	4.1	•40	....	....	•1.7	....	•14	•143	•11	....
39	P	De Cal Mtp So Frs Kp Sc	730	3.4	•19	....	....	....	....	....	•12	....	....
40	P & H	De Cail Te Mt So De Ke So Frs Dx Sc	730	.8	•18	....	•22	....	....	[4]4.6	•175	....	....
41a	P & H	De Cls Ne Mb Sm R So Ke Frs } Sc Ne Dx											
41b	P & H	De Cls Mt Cs R M Sm Ke Frs } Sc Ne Dx	730	38.0	•28	....	....	....	....	•.2	•186	•36	....
42	P	Cal Mt De Mp So Dd Frs Kp Sc De	730	40.0	•15	....	....	....	....	....	•17	....	•1
43	P & H	De Cs Mt So Cls Mp Sm So R Frs Sc De	731	7.4	•30	....	....	....	....	....	•96	•14	(X)
44	P & H	Te Cail Mb (MtpsSv) So De Frs Sc Dd	730	1.6	[1]18	....	•24	....	....	•2.2	•106	....	....
45	P & H	Dx Mi Cal Mt Cs Te Mp S R Frs Ke Sc De	639	.1	40	....	....	....	....	•20.0	•204	•140	•(X)
46	P	As Cs Te M De S Kp Frs (MtpsSvFrs) De Sc	730	12.0	•14	....	....	....	....	•9	•16	....	....
47	P	De Cs Te Mbp So Frs De Sc	730	6.6	•20	....	....	....	....	[7]1.8	....	....	....
48	P	De So Cat Te Mpb Cls Sm R Frs Ne De Sc	730	71.0	•12	....	....	....	[7]1.7	•6	•28	•28	(X)
49	P	De Cs So Cli Te Mhp Sm Frs Ng De Kp Sc	730	86.0	[4]11	....	•13	....	....	•3	•15	•8	....
50	P & H	De Cil Te Mtp Sm Frs Kp Sc De	683	42.0	•5	....	•13	....	....	•6	•96	....	....
51	P	Ng De Cs Te Mp So Frs Kp Sc De	730	51.0	•24	....	....	....	....	•1.3	•7	....	....
52	P	De Cal Mb S (MtpsSv) Frs Ng De Mb Sc	730	30.4	•18	....	....	....	....	•X	•6	....	....
53	P & H	Cals Mtb Sm R So Frs De(x) So Ke	730	51.0	•30	....	....	....	....	....	•169	•75	•(X)
54	P	De Cal Te MtpSo(Te) Frs De (Dd) Sc	731	7.4	•26	....	....	....	....	•1.5	•4	....	....
S-1	P	So Cs Te Ne De So Ne De So	730	10.0	20	....	....	....	....	•1.2	....	....	....
C-1	D	De Mi	730	10.4	....	....	....	....	....	....	....	....	....
C-2	D	Ng De	1,039	17.0	....	....	....	....	....	....	....	....	....
C-3	D	De Kep	97	8.4	....	....	....	....	....	....	•4	....	....

[0] Applied 5 percent of time.
[1] Applied 5–15 percent of time.
[2] Applied 15–25 percent of time.
[3] Applied 25–35 percent of time.
[4] Applied 35–45 percent of time.
[5] Applied 45–55 percent of time.
[6] Applied 55–65 percent of time.
[7] Applied 65–75 percent of time.
[8] Applied 75–85 percent of time.
[9] Applied 85–95 percent of time.
• Applied ≥ 95 percent of time.
X Used at least part time.
? Understood to be used, but data not available.

TABLE 2.—*Treatment plant facilities and average chemical dosages—continued*

Plant Code number	Type of plant	Treatment facilities and chemicals	Days of record	Complex Phosphate, mg/l	Chlorine: Pre mg/l	Chlorine: Interm mg/l	Chlorine: Post mg/l	Chlorine: Total mg/l	Ammonia: Anhydrous, mg/l	Ammonia: Other, mg/l	Sodium chlorite, mg/l	Others: Dosage, mg/l	Others: Chemical
1	P	So Ng Dc Cas Mtb So Frs Sc	730		2.0			2.0	0.2				
2	P & H	Ng Dc Cil (MtpsSv) Frs Dc Sc	361		(X)		(X)	2.6	(?)				
3	P & H	Cl Mb So Ci Dc (MtpsSv) Kc So Frs Sc	730	2.2	14.5			14.5					
4	P	Ng Dc Ca Tc Mp So Frs Dc Kp Sc	730		(X)		(X)	.9	.2				
5	P	Mh Sm Calt Mbp Sm Dc Mtp So Frs Sc Nc Dc	731		4.0		0.2	4.2		0.5			
6	P	So Cal Tc Mtp Sm Dc So Frs Sc Dc	730		3.6		.7	4.3					
7	P & H	Nc Dc Cat Tc As Cl (MtpsSv) Ca Tc Mtp Sc R Frs(a) Nc Dx Sc	730		3.0		.7	3.7		2.3	0.2		
8	P	Dc Cal Mtp Sc Frs Kp As Sc Dc	719		2.6		.2	2.6					
9	P & H	Ng Dc Cal Tc Mtp Smo R Frs Dc Kc Sc	730	1.3	2.3		2.3	4.6	1.1				
10	P	Tc Ca As So Dc So Frs Kc Dx Sc	730	2.9	3.6		.8	4.4			.3		
11	P	Dc Cas Mtp Sm Frs Dc Kp Sc	699		3.2		.2	3.4					
12	P & H	Sm Nc Dc Cails Mbp Tc Cai Mp S R Dc Frs Sc	731		(X)		(X)	1.6		1.1			
13	P & H	Dc Sm Cals Dc Mtp Sm R Ca So R Frs(a) Sc Nc	731	.2	11.4			11.4		1.3			
14	P	Dc Ca Tc Mb So Kp Frs Dx Sc	730		2.2		.2	2.4			.1		
15	P & H	Sc So Cails Mb Sm R Tc S R Frs Dc So Dd Fac Kp Ng Dc	624	4.0	3.5		1.2	4.3	1.7	2.7		(X)	SO_2
16	P	Dc Ca Mtp Scm Dc Frs Nc Sc	731		3.2	(X)		3.2		.6		(?)	$NaHSO_3$
17	P	Dc Ca Mtps Sv (MiSo) Dc Frs (Fs) Sc	731		4.2	1.0		5.2					
18a	P	Dc Ca Mp Sm Frs Dc } Sb.	681		6.0		.3	6.3					
18b	P	Nc Dc Ca So Nc Dc So Fr Dc } Sb.	730		5.0	.7	.3	5.9		1.4			
19	P & H	Cals Mb (MtpsSv) R Cas Nc Tc Mb Dc So Frs Ng Dc Sc	730			4.2	.4	4.6	.1	3.4			
20	P	Dc Ca Mb Tc Sc Dx Frs Sc	730		3.0		.2	3.2			.2		
21	P	Dc Ca Tc Mb So Kp Frs Dx Sc	730		2.1		.3	2.4			.1		
22	P	Dc Cas Mip So Frs Ng Dc Sc	730		2.6		.6	3.2	.1				
23	P	A Dc Cil (MtpsSv) Dx Frs Dx Sc	730		(X)	(X)	(X)	5.3			3.6		
24	P	So Dc Cal Mb So Tc Mb Ca Mb So Dc Frs Dc So	730		3.6	.6	.2	4.0					
25	P	So Cal Dc Mib So Frs Dc Kp Sc	730		7.1			7.1					
26	P	Cal M So Frs Kc Nc Dc(x) Sc	731	.4			1.2	1.2		.6			
27	P & H	Tc Cal Mbp Sm Ci Dc Tc Mtp Sm R Dc Frs Sc	730	X	3.6	.4		3.8	.3		.5		
28	P	Dc Ca Mib So Frs As Fs Kp Sc Dc	730		5.6		.1	5.7					
29	P	Nc Dc Ca Tc Mi So Frs Kp Sc Dx Sc	730		1.2		1.2	1.9		.4	.1		
30	P	Dc Ca Tc Mi A Cl So Mp So Frs Sc Dx Sc	730		1.6		.3	1.9			.3		
31	P	Ca Mp So Cal Dc Mtp Sm Frs Dx Sc	729		.8		.4	.6			.2		
32	P & H	So Cail Mb Sm Nc Dc Ca Mb Sm Frs Nc Dc Sc	731		1.4		1.2	2.6		.4			
33a	P	A Cail Mtp Sm } A Cal Mtp S Mtp Dc Sm Dc Frs Sc Dc											
33b	P	A Cail Mtp Sm } Cal Mtp Dc Sm Dc Frs Sc Dc	730		(X)	(X)	(X)	7.0					
34	P & H	So Cl Mt Cai Mb Sm Cai Mb Cai Nc Dc Sm Dc Frs Sc	731		1.4		1.0	2.4		1.4			
35	P	So Cal M So Frs Sc N Dc(x) Sc	731				1.2	1.2		.6	.2		

36	P & H	Cl So Ne Dc Ci Mip So Ci Mp So Ci Ne Dc Frs Se	731	...	•2.2	...	•.3	•2.5	...	•.9	...	...	
37	P	Ne Dc Cat Mop So Frs Kp Se	730	...	•2.9	...	...	•2.9	...	•.6	...	...	
38	P & H	Dc Cat Mb So Cl Mt Sm R Dd Ne Dc So Frs Se	629	...	•8.4	...	...	•8.4	...	•2.5	...	•2.0	$Na_2S_2O_4$
39	P	Dc Cal Mtp So Frs Kp Se	730	...	•2.2	...	...	•2.2	...	...	...	...	
40	P & H	Dc Cail Te Mt So Dc Ke So Frs Dx Se	730	[4]X	•6.0	...	•0.6	•6.6	...	...	•.5	...	
41a	P & H	Dc Cls Ne Mb Sm R So Ke Frs } Se Ne Dx											
41b	P & H	Dc Cls Mt Ca R M Sm Ke Frs } Se Ne Dx	730	•.8	•6.6	[1]1.9	•.3	•6.4	...	•1.4	•.3	...	
42	P	Cal Mt Dc Mp So Dd Frs Kp Se Dc	730	...	•7.6	...	•.3	•7.9	...	...	...	[4]3.5	SO_2
43	P & H	Da Ca Mt So Cls Mp Sm So R Frs Se Dc	731	...	[2]0.3	...	•.8	•1.1	...	...	...	...	
44	P & H	Te Cail Mb (MtpsSv) So Dc Frs Se Dd	730	...	...	•3.6	...	•3.6	...	...	...	•2.0	SO_2
45	P & H	Dx Mi Cal Mt Ca Te Mp S R Frs Ke Se Dc	639	•1	•9.6	...	...	•9.6	...	...	[7]1.1	...	
46	P	As Ca Te M Dc S Kp Frs (MtpsSvFrs) Dc Se	730	...	•.3	...	•1.7	•2.0	...	...	...	...	
47	P	Dc Ca Te Mbp So Frs Dc Se	730	...	•.5	...	•.3	•.8	...	...	...	...	
48	P	Dc So Cat Te Mpb Cls Sm R Frs Ne Dc Se	730	...	•4.9	...	•.4	•5.3	•.5	...	[3].3	...	
49	P	Dc Ca So Cli Te Mbp Sm Frs Ng Dc Kp Se	730	...	•8.0	...	•.3	•8.2	•.2	...	...	...	
50	P & H	Dc Cil Te Mtp Sm Frs Kp Se Dc	683	...	[7]2.3	...	•1.5	•3.1	•.4	...	...	...	
51	P	Ng Dc Ca Te Mp So Frs Kp Se Dc	730	...	•1.5	...	•.2	•1.7	•.2	...	...	...	
52	P	Dc Cal Mb S (MtpsSv) Frs Ng Dc Mb Se	730	...	•.7	...	•1.0	•1.7	•.3	...	...	...	
53	P & H	Cals Mtb Sm R So Frs Dc(x) So Ke	730	•0.6	...	...	•.3	•.3	...	...	•.1	...	
54	P	Dc Cal Te MtpSo (Tc) Frs Dc (Dd) Se	731	...	•2.6	...	•.1	•2.6	...	...	...	•(X)	SO_2
S-1	P	So Ca Te Ne Dc So Ne Dc So	730	...	•4.0	...	...	•4.0	...	•2.8			
C-1	D	Dc Mi	730	...	...	...	•1.7	•1.7	...	...			
C-2	D	Ng Dc	1,039	...	...	...	•1.5	•1.5	•.1	...			
C-3	D	Dc Kcp	97	•1.8	...	...	•2.4	•2.4	...	...			

[0] Applied 5 percent of time.
[1] Applied 5–15 percent of time.
[2] Applied 15–25 percent of time.
[3] Applied 25–35 percent of time.
[4] Applied 35–45 percent of time.
[5] Applied 45–55 percent of time.
[6] Applied 55–65 percent of time.
[7] Applied 65–75 percent of time.
[8] Applied 75–85 percent of time.
[9] Applied 85–95 percent of time.
[e] Applied ≧ 95 percent of time.
X Used at least part time.
? Understood to be used, but data not available.

KEY FOR TREATMENT
FACILITIES AND CHEMICALS USED IN
TABLE 2

Type of Plant
P—Purification
H—Softening
D—Disinfection

Treatment or Device
A—Aeration
  As..spray aerator
C—Chemical dosage for coagulation or softening
  Ca..alum
  Ci..iron salts
  Cl..lime
  Cs..soda ash
  Ct..activated silica
D—Disinfection
  Dc..chlorine gas
  Dd..dechlorination
  Dx..chlorine dioxide
F—Filters
  Fa..anthrafilt
  Fc..roughing or contact
  Fr..gravity (rapid)
  Fs..sand
K—Chemical dosage for corrosion correction or water stabilization
  Kc..phosphate compounds
  Kp..alkali feed for pH adjustment
M—Mixing device or tank
  Mb..baffle mix
  Mh..hydraulic (standing wave flume)
  Mi..injection or pump suction
  Mp..slow mechanical mix
  Ms..patented sludge blanket
  Mt..rapid mechanical mix
  (MtpsSv).."Liquon Reactor"; "Accelator"; or "Precipitator"
N—Ammoniation
  Nc..ammonium compound
  Ng..ammonia gas
R—Recarbonation
S—Sedimentation
  Sc..covered basins (other than housed)
  Sm..mechanical sludge removal
  So..open basin (may be in plant building)
  Sv..upflow cylindrical tanks
  (MtpsSv).."Liquon Reactor"; "Accelator"; or "Precipitator"
T—Chemical taste and odor control
  Tc..activated carbon

3.33 ml plantings [abbreviated form for writing three 1-ml, three 0.1-ml, and three 0.01-ml portions (11)] were positive, the MPN has been assumed to equal or exceed that for 3.330 ml positives, or ⋝24,000 per 100 ml. Likewise, if all portions of the 3.33 ml plantings were negative, the MPN has been assumed to be ⋜23. Average bacterial densities include such data. Where practical, averages including indeterminates due to all portions being positive, or all portions being negative, have been prefixed by a sign, ⋝ or ⋜. Those containing both high and low indeterminates have been prefixed by a ± sign.

The bacteriological data for filter effluent samples are confirmed test data unless otherwise noted. Usually they are the results from examining one or more portions in each of two or more decimal volumes.

Samples of plant effluent, and sometimes of filter effluent, were taken daily at most plants. Usually five 10-ml portions were examined by either the confirmed or completed test. Several plants also examined 100-ml and 1-ml portions. Sometimes two or more samples were taken during the day. For example, one plant examined one 100-ml portion of each of 12 samples daily. All results on these individual samples are indeterminate, being either ⋝ or ⋜1 per 100 ml. In such cases an average MPN for the day has been calculated by considering the results from the individual samples as those from a single daily composite, or as twelve 100-ml portions of a single sample and the MPN has been computed by the formula:

$$\text{MPN per 100 ml} = \frac{230}{N} \log_{10} \left(\frac{K}{q}\right)$$

where

N=volume of portion (ml)

K=total number of portions

q=total number of portions negative

For plants examining only 100-ml portions of plant effluent, the percentage of 10-ml positive portions has been estimated by using the above formula to solve for the number of positive 10-ml portions giving the same MPN as that obtained for the 100-ml portions. Also in a few cases an average MPN for a group of samples has been estimated using the above formula. Such a method has been combined with Thomas's (12) log-probability procedure to approximate an average MPN for filter effluent at each of two plants that examined 1-ml portions only.

For computing averages of MPN for filtered and finished water, values <2.2 per 100 ml (no positives in five 10-ml plantings) have been considered to be 0 per 100 ml; however, indeterminates such as all positive portions in a 51.0 planting have been taken as $\geqq 240$ per 100 ml.

COLIFORM BACTERIAL OBJECTIVE FOR WATER TREATMENT PLANT EFFLUENT

The Public Health Service Drinking Water Standards are those generally accepted for potable water in this country. These Standards specify that the bacterial quality of the water shall be based on a variable number, determined by the population served, of samples collected from representative locations throughout the distribution system. Compliances with the *Public Health Service Drinking Water Standards* cannot be determined using bacteriological data for plant effluent samples only.

On the other hand, plant performance cannot be based on the bacterial quality of samples taken from various locations throughout the community. Inclusion of such data would reflect a change in bacterial quality that might occur in the distribution system and not permit a true evaluation of the treatment processes.

The coliform bacterial objective for water plant effluent used in this paper is that not more than 2 percent of all 10-ml portions of plant effluent examined during any one month shall be positive for coliform organisms. This objective has been selected after analysis of the data presented. Not only is conformance to this objective readily obtainable, but in the opinion of the author, all plants failing to produce waters meeting this objective had deficiencies in either facilities or operation.

SIMPLE CHLORINATION

The Public Health Service has recommended (1) that the average coliform bacterial density during any month should not exceed 50 per 100 ml for a surface water to be acceptable for treatment by simple chlorination. This recommendation has been adopted by various state and other agencies. Most of the data (2) (3) (4) upon which the recommendation was based was from marginal postchlorination of pretreated (coagulated, settled, and filtered) waters to provide total residual chlorine concentrations between 0.05 and 0.1 mg/l. The applicability of such data to either unfiltered surface water or to water chlorinated to provide a substantial free chlorine residual may be questionable.

Collection of Data

Although a special effort was made to locate plants having adequate data for study of the effectiveness in reduction of coliform bacteria by chlorination of untreated surface waters, only 4 plants were found where the monthly average coliform density in the raw water exceeded 50 per 100 ml. Two or three years of data from each of three plants using simple chlorination, and from three filtration plants using only postchlorination have been analyzed.

Plants Studied

Plant C–1 treated an average of 10 mgd of Great Lakes water. The turbidity usually did not exceed 10, but occasionally reached 100 units. Data for pH and temperature were not available. Treatment consisted of chlorination. The amount applied ranged from 1.1 to 2.9, and averaged 1.7 mg/l. Residual chlorine concentrations determined by the Laux flash test averaged 1.0 mg/l on samples taken after a theoretical contact time estimated to be 20 minutes. Minimum daily residuals of 0.7 and 0.2 mg/l were recorded during 1953 and 1954, respectively.

Raw and chlorinated water samples were examined by the County-City Health Department 5 or 6 days per week. Coliform bacterial examinations of raw water samples were made using 11.1 ml plantings, confirmed test; and for the chlorinated water with five 10-ml portions, confirmed test. Except for use of single-strength broth for 10-ml plantings, bacteriological laboratory procedures were satisfactory.

Plant C–2 used water from a mountain stream as one of its sources of supply. When water from this source was used the average amount treated was approximately 17 mgd. Normally, the turbidity was less than 5 units. It exceeded 10 units during only 8 of 35 months. The maximum recorded turbidity was 38 units. The pH was consistently recorded as 8.0. The water temperatures varied with the seasons, ranging from 32° to 55° F.

Treatment consisted of adding ammonia and chlorine. Average dosages were 1.5 mg/l chlorine and 0.12 mg/l ammonia. A continuous recorder was used to measure the total residual chlorine, which averaged 0.7 mg/l after approximately 20 minutes contact. Minimum daily averages showed only 0.3 or 0.4 mg/l.

Raw and chlorinated water samples usually were examined 5 days each week by the City Health Department. Coliform bacterial examinations of raw water were made using 55.5 ml plantings, confirmed test; and for the chlorinated water by five 10-ml plantings, completed test. Bacteriological laboratory procedures conformed with *Standard Methods*.

Plant C–3 treated 4 to 20 mgd of impounded water. Turbidity ranged from 0 to 20 units, and did not exceed 5 for 94 percent of the determinations. This was a soft water with a pH ranging from 6.3 to 6.9, and averaging 6.6. Temperature varied seasonally from 34° to 71° F. Treatment consisted of chlorination, also the addition of lime and calgon to prevent corrosion and deposition in mains. Chlorine additions ranged from 1.2 to 4.0, and averaged 2.4 mg/l. The total chlorine residual after 10 minutes contact time, as determined by a continuous recorder, averaged 1.3, with a minimum of 0.9 mg/l. That determined from one of two other locations, which provided an average contact time estimated to be either 20 or 60 minutes, usually ranged from 0.1 to 0.3 mg/l. However, 0.0 mg/l residuals frequently occurred.

Bacteriological data for raw and chlorinated waters were based on samples taken once each week. Raw water coliform densities were determined by examining 51.1 ml plantings, confirmed test, and those for the chlorinated water by five 10-ml plantings, completed test, using samples from either one or both of two locations. Bacteriological laboratory procedures conformed to *Standard Methods*.

Operational procedure used at three conventional rapid sand filtration plants permitted study of the effect of chlorination on clarified and filtered waters.

Plant 26 postchlorinated filter effluent with an average dosage of 1.2 mg/l. The pH of the water ranged from 6.9 to 7.7, and averaged 7.4. The temperature of the raw water varied from 33° to 87° F, according to the season. Total residual chlorine level in the plant effluent ranged from 0.2 to 1.0, and averaged 0.4 mg/l. This was after a theoretical contact time varying between 2.5 and 5 hours.

Samples of filter and plant effluents were taken daily. Coliform examinations of filter effluents were made using one 1-ml portion, confirmed test and of plant effluent, using five 10-ml portions, confirmed test.

Plant 35 secured water from the same source as Plant 26. The coagulated, settled, and filtered water was treated with an average of 1.2 mg/l of chlorine. This water had a pH ranging from 6.9 to 8.0 and averaging 7.5. The raw water temperature varied from 32° to 87° F. Daily total residual chlorine levels, after a theoretical contact time between 0.9 and 1.7 hours, averaged 0.5 and ranged from 0.3 to 1.0 mg/l.

Samples of filter and plant effluents were examined daily. Procedures were identical to those reported for Plant 26 except that the presumptive test only was used for examining the filter effluent.

At Plant 53 the effluent from the filter had been treated by coagulation, sedimentation, and excess lime-soda softening followed by secondary sedimentation and recarbonation. The softening process resulted in water of high pH. That for the plant effluent ranged from 9.1 to 10.9 and averaged 10.3 for the 2-year period. Raw water temperatures varied from 32° to 80° F.

Disinfection was by marginal postchlorination. Chlorine dosages varied from 0.1 to 0.8 mg/l for daily averages; from 0.2 to 0.6 for monthly averages, and averaged 0.3 for the 2-year period. The total residual chlorine concentration as determined on samples taken after a theoretical contact time ranging from 5 to 10 hours varied from a trace (<0.05) to 0.3 mg/l. They equaled or exceeded 0.1 mg/l 60 percent of the time, but 0.2 mg/l only 1.9 percent of the time.

Samples of filter and plant effluents were collected daily. These were examined for coliform bacteria using 51.0-ml plantings, confirmed test, for the filter effluent, and five 10-ml portions, confirmed or completed test, for the plant effluent.

Discussion

Data from 3 plants totaling 84 months and 1,304 days for which both raw and chlorinated water bacteriological records were available, and also that from three conventional rapid sand filtration plants adding chlorine to filter effluent only, have been examined.

In table 3, the plant months for each of the three simple chlorination plants are classified by monthly arithmetical average raw water coliform density. Then the total months in each group are compared to the number of months during which coliform bacteria were detected in one or more of the chlorinated water samples. The greatest monthly average densities in the raw water

TABLE 3.—*Effectiveness of simple chlorination in the reduction of coliform bacteria, monthly data*

Range, monthly average MPN per 100 ml	RAW WATER—Coliform density				CHLORINATED WATER—Months during which coliform-positive samples were detected[a]	
	Frequency, months					
	Plant C–1	Plant C–2	Plant C–3	All plants	Number	Percent
0– 24	14	7	13	34	4	12
25– 49	6	10	1	17	2	12
50– 99	4	15	6	25	2	8
100–240	....	3	3	6	0	0
250–490	....	1	0	1	0	0
$\geq$500	....	....	1	1	0	0
Total or avg.	24	36	24	84	8	10

[a] All coliform positive samples occurred at Plant C-1.

were $\geq$98, 340, and $\geq$660 per 100 ml at Plants C–1, C–2, and C–3, respectively. The monthly average coliform loadings for raw water exceed 49 per 100 ml during 39.3 percent of the time, and 99 per 100 ml during 9.5 percent of the time.

Coliform bacteria were found in the chlorinated water in only 8 samples, all from Plant C–1. Each coliform positive sample occurred in a different month. The detection of coliform bacteria at Plant C–1 only cannot be explained on either the basis of raw water loading or the reported chlorine residuals. It may be significant that both the facilities and technical supervision were considered inferior at this plant. For example, chlorination facilities consisted of two 200 lb/day chlorinators.[2] Failure of one of these units during a period of peak flow would result in less than average chlorine application. It was also observed that a residual chlorine recorder installed at this plant had not been maintained and was inoperative. However, during 23 of the 24 months of record less than 2.0 percent of all 10-ml portions of chlorinated water examined were positive for coliform bacteria. For the month of poorest plant effluent only 2.3 percent of the 10-ml portions examined were coliform positive.

Table 4 groups the daily data according to the coliform bacteria in the raw water and compares the frequencies with which coliform were detected in the chlorinated water for the various groups. Although the coliform densities in the raw water varied from $\leq$2.3 to $\geq$2400 per 100 ml at each plant, there were only 22 days during which they exceeded 240 per 100 ml. There appear to be no significant differences in the effectiveness of chlorination for daily coliforms loadings ranging from 0 to 240 per 100 ml.

The filter effluents at Plants 26 and 35 contained coliform bacteria in 49 and 87 percent, respectively, of the 1-ml portions examined. If the results from each plant are considered as those

[2] Plant C–1 has since corrected this situation by the installation of two chlorinators having 400 lb/day capacity.

TABLE 4.—*Effectiveness of simple chlorination in the reduction of coliform bacteria, daily data*

Range, daily MPN per 100 ml	RAW WATER—Coliform density: Frequency, days				CHLORINATED WATER—Days on which Coliform-positive samples were detected[a]	
	Plant C–1	Plant C–2	Plant C–3	All plants	Number	Percent
0– 24	501	322	61	884	4[b]	0.5
25– 49	....	172	21	193	0	.0
50– 99	....	59	0	59	0	.0
100–240	40	91	15	146	2[c]	1.4
250–490	....	17	0	17	0	.0
500–990	....	1	0	1	0	.0
≥1000	1	2	1	4	0	.0
Total or average	542	664	98	1,304	6	.5

[a] At Plant C-1, coliform bacteria (MPN of 2.2 per 100 ml) were detected in 2 samples of chlorinated water examined on days for which raw water data were not available.
[b] Coliform densities 9.2, 5.1, 2.2 and 2.2; avg. 4.6 per 100-ml.
[c] Coliform densities 2.2 and 2.2; avg. 2.2 per 100-ml.

from a single sample, the estimated 2-year average most probable numbers would be 67 and 205 per 100 ml, respectively. The average coliform density of the filter effluent at each of these two plants has also been computed by assuming the bacteriological results from each examination of 10 consecutive 1-ml portions as representing the result from a single sample, and then applying Thomas's log-probability procedure (12) to obtain an average value. This procedure gives 2-year average most probable numbers of 77 and 249 per 100 ml for plants 26 and 35, respectively. No coliform bacteria were detected at either plant on examination of 731 samples of the chlorinated plant effluents by planting five 10-ml portions of each sample.

In analyzing the coliform bacteria data for Plant 53, shown in table 5, it should be remembered that the final treatment consisted of marginal chlorination, with the chlorine application averaging only 0.3 mg/l, of a lime-soda softened water having a high pH. In contrast to the data previously discussed, both the frequency of detection and average density of coliform bacteria in the plant effluent increase directly with the coliform loading in the filtered water. Insofar as it could be determined, the variations in daily average residual chlorine concentration (trace to 0.29 mg/l) had little effect on the coliform density in the plant effluent.

Conclusions

The available data are insufficient to draw general conclusions. Two of the three simple chlorination plants treated surface waters containing monthly average coliform loadings in excess of 50 per 100 ml to produce water meeting the assumed bacteriological objective for plant effluent. The limited data indicate that it is possible to treat waters containing somewhat higher loadings.

TABLE 5.—*Effectiveness of marginal chlorination of filtered water, high in pH, in the reduction of coliform bacteria, daily data, Plant No. 53*

FILTER EFFLUENT—Coliform-density[a]		PLANT EFFLUENT								
		Total chlorine residual		Number of days on which coliform density[b], MPN per 100 ml, was:						Coliform density[c], Avg. MPN/100 ml
Daily MPN per 100 ml	Frequency Days	Range in concentration mg/l	Frequency, days	<2.2	2.2	5.1	9.2	16	≥23	
<2.2	608	0.00–0.09	251	247	3	1	.....	.....	.....	0.06
		0.10–0.19	347	336	10	1	.....	.....	.....	
		0.20–0.29	10	10	.....	.....	.....	.....	.....	
2.2	68	0.00–0.09	19	19	.....	.....	.....	.....	.....	.10
		0.10–0.19	49	46	3	.....	.....	.....	.....	
		0.20–0.29	0	.....	.....	.....	.....	.....	.....	
5.0	19	0.00–0.09	6	6	.....	.....	.....	.....	.....	.11
		0.10–0.19	13	12	1	.....	.....	.....	.....	
		0.20–0.29	0	.....	.....	.....	.....	.....	.....	
8.9	12	0.00–0.09	3	3	.....	.....	.....	.....	.....	.76
		0.10–0.19	9	8	.....	.....	1	.....	.....	
		0.20–0.29	0		.....	.....	.....	.....	.....	
16	4	0.00–0.09	2	2	.....	.....	.....	.....	.....	.0
		0.10–0.19	2	2	.....	.....	.....	.....	.....	
		0.20–0.29	0	.....	.....	.....	.....	.....	.....	
39	12	0.00–0.09	2	2	.....	.....	.....	.....	.....	≥4.0
		0.10–0.19	8	5	1	.....	.....	.....	2	
		0.20–0.29	2	2	.....	.....	.....	.....	.....	
≥240	7	0.00–0.09	0	.....	.....	.....	.....	.....	.....	5.6
		0.10–0.19	5	3	.....	1	1	.....	.....	
		0.20–0.29	2	.....	.....	.....	1	1	.....	
Total or average	730		730	703	18	3	3	1	2	≥0.20

[a] Filter effluent samples examined daily using 51.0-ml plantings, completed test.
[b] Plant effluent samples examined daily using five 10-ml portions, completed tests.
[c] For purposes of averaging, if all five 10-ml portions were negative the MPN was assumed to be 0 per 100 ml; if all were positive, it was assumed to be ≥ 23 per 100 ml.

The data on postchlorination of a filtered water from a single plant confirm the relative ineffectiveness of marginal postchlorination of water of high pH as noted by Butterfield (13).

Treatment only by chlorination requires continuous operation. Adequate standby chlorinators are essential and continuous residual recording equipment provided with an alarm system is very desirable.

CONVENTIONAL RAPID SAND FILTRATION AND DISINFECTION

Plants Studied

Plant records have been analyzed from 54 of the more than 80 water filtration plants visited. Data from certain plants have been rejected for the following reasons: (a) Raw water coliform bacterial density less than 5,000 per 100 ml for month of maximum loading; (b) numerous indeterminates due to inadequate dilutions in bacteriological examination of raw water; (c) insufficient bac-

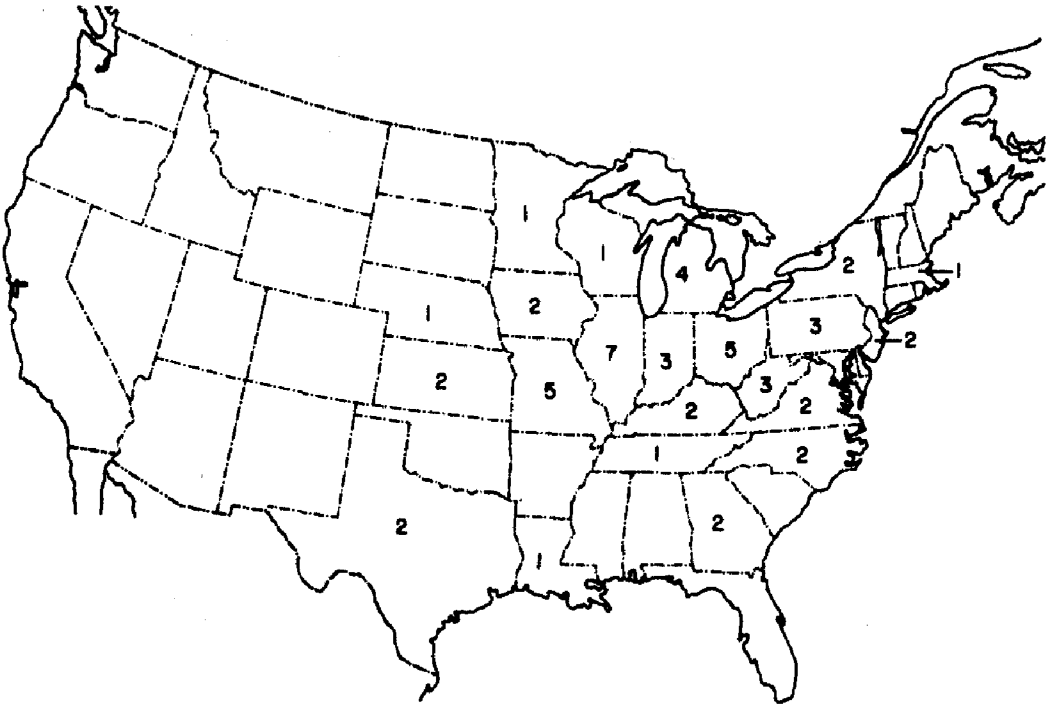

Figure 1. Geographical Distribution of Water Filtration Plants

teriological data for raw water; (d) unsatisfactory bacteriological laboratory procedures; and (e) obvious errors in plant records.

The geographical distribution of the 54 plants is shown in figure 1. All provided at least chemical coagulation, sedimentation, filtration, and disinfection. Several provided additional treatment such as multistage coagulation and sedimentation, excess lime or lime-soda softening, taste and odor control, and corrosion control.

The sizes of these plants are indicated by table 6, which groups them according to average daily water production for the 2-year period. The smallest plant produced slightly less than 100,000 gpd; the largest more than 100 mgd.

In table 7 the plants are classified according to the annual average total chlorine application and the location at which chlorine (as chlorine, chloramine, or chlorine dioxide) was first applied. For the purpose of classification, prechlorination includes any addition of chlorine providing substantial contact time prior

TABLE 6.—*Sizes of the water filtration plants*

Average water production, mgd	Number of plants
0.1– 0.9	2
1.0– 4.9	20
5.0– 9.9	12
10–24	3
25–49	9
≥50	8
Total	54

TABLE 7.—*Chlorination practices at the water filtration plants*

Total chlorine application, mg/l	Number of plants at which chlorine was first applied as:			Number of plants applying indicated chlorine dosage
	Pre-chlorination	Intermediate chlorination	Post-chlorination	
0.1-0.9	2	0	2	4
1.0-1.9	5	0	3	8
2.0-2.9	12	0	0	12
3.0-3.9	7	1	0	8
4.0-4.9	6	1	0	7
5.0-9.9	13	0	0	13
≧10	2	0	0	2
Total	47	2	5	54

to filtration; intermediate chlorination, the addition of chlorine immediately prior to filtration; and postchlorination, any addition of chlorine after filtration. At least 24 of these plants normally applied chlorine at two or more locations.

The plants are grouped in tables 8 and 9 according to the average residual chlorine in their effluents. In most cases only total residual chlorine was reported, but some plants reported free

TABLE 8.—*Residual chlorine concentrations in effluents from 32 water filtration plants using chlorine disinfection*

Residual chlorine concentration, mg/l	Number of plants reporting[a]—			
	Free chlorine residual		Total chlorine residual	
	Annual average	Minimum daily average	Annual average	Minimum daily average
≦ 0.04	0	3	0	3
0.1	2	1	[b]2	5
0.2	1	4	0	4
0.3-0.5	2	3	8	8
0.6-0.9	4	1	10	3
1.0-1.9	3	0	4	2
≧ 2.0	0	0	1	0
Totals	12	12	25	25

[a] Five plants reported both free and total residual chlorine concentrations. At three plants chloramine disinfection was used during one of the two years included in this study.
[b] Plants 44 and 58.

TABLE 9.—*Residual chlorine concentrations in effluents from 25 water filtration plants using chloramine disinfection*

Residual chlorine concentration, mg/l	Number of plants reporting[a]—			
	Free chlorine residual		Total chlorine residual	
	Annual average	Minimum daily average	Annual average	Minimum daily average
≦ 0.04	0	4	0	0
0.1-0.2	2	0	0	5
0.3-0.5	2	0	4	7
0.6-0.9	0	0	9	7
1.0-1.5	0	0	5	5
1.6-1.9	0	0	4	0
≧ 2.0	0	0	3	1
Totals	4	4	25	25

[a] Four plants reported both free and total chlorine residuals.

chlorine and a few both free and total. It is significant to compare the chlorine residuals maintained at these plants with the low total chlorine residuals (apparently around 0.05 mg/l practiced at the time of Streeter's studies for the Public Health Service.

Discussion

In table 10, data from 54 plants totaling 107 plant years are grouped according to the annual arithmetical average density of coliform bacteria in the raw water. These ranged from 1,100 to 1,700,000 per 100 ml. Each group is then subdivided according to

TABLE 10.—*Effectiveness of conventional rapid sand filtration and disinfection water plants in the reduction of coliform bacteria, annual data*

RAW WATER—Coliform density		PLANT EFFLUENT—Plant years during which the percentage of coliform-positive 10-ml portions was[a]			
Annual Range, average MPN per 100-ml	Frequency plant years	0.00	.01-.09	0.1-0.9	≥1.0
0- 4,900	17	8	3	5	1
5,000- 9,900	17	9	4	3	1
10,000- 24,000	32	26	5	1	0
25,000- 49,000	25	19	3	3	0
50,000- 99,000	11	7	2	2	0
100,000-490,000	1	1	0	0	0
500,000-990,000	2	2	0	0	0
≥1,000,000	2	1	1	0	0
Totals	107	73	18	14	2

[a] For plants examining only 100-ml portions of plant effluent, the percentage of positive 10-ml portions giving the same MPN has been used.

the percentage of treated water portions which were found positive for coliform organisms. Coliform bacteria were detected in the plant effluent, during 50 percent of these plant years in which raw water loadings were less than 10,000 per 100 ml; but in only 32 percent of all plant years in which the loadings were less than 100,000 per 100 ml. There are only two plant years during which the number of 10-ml portions of finished water, which were positive for coliform bacteria, equaled or exceeded 1 percent of those planted. Both occurred with raw water bacterial loadings less than 10,000 per 100 ml.

Data for all plant years in which coliform organisms were detected in 0.2 or more percent of all 10-ml portions of finished water examined during the year are given in table 11. For coding purposes the plants have been numbered in the order of decreasing annual average density of coliform organisms in the raw water. Four of the plants (Nos. 8, 24, 44, and 53), data from which appear in this table, will be discussed in some detail later.

Data for 1,281 plant months are grouped according to monthly arithmetical average density of coliform bacteria in the raw water in table 12. The maximum monthly density recorded was

TABLE 11.—*Coliform bacterial data for raw and finished waters at conventional rapid sand filtration and disinfection water plants for all years during which 0.2 or more percent of the 10-ml portions of plant effluent examined were positive for coliform bacteria*

Plant code number	Year	RAW WATER—Coliform density, annual average MPN per 100 ml	PLANT EFFLUENT—10-ml portions	
			Number examined	Percent positive
8	1954	[a,c]59,000	1,250	0.72
15	1954	[b,c]39,000	[d]1,565	[e].27
24	1954	[c]28,000	1,825	.88
44	1953	[c]6,800	918	.22
	1954	[c]6,700	912	.98
53	1954	[a,c]2,300	1,825	.93
	1953	[a,c]1,100	1,825	1.76

[a] MPN by Thomas's approximate method. (10)
[b] Direct planting into BGD lactose broth.
[c] Confirmed test.
[d] 100-ml portions.
[e] Percentage of 10-ml portions giving same MPN per 100 ml as percentage of positives resulting from 100-ml portions.

TABLE 12.—*Effectiveness of conventional rapid sand filtration and disinfection water plants in the reduction of coliform bacteria, monthly data*

RAW WATER—Coliform density		PLANT EFFLUENT—Plant months during which the percentage of coliform-positive 10-ml portions was[a]			
Monthly Range, average MPN per 100 ml	Frequency, plant months	0.0	0.1-0.9	1.0-1.9	≥2.0
0- 4,900	339	310	19	3	7
5,000- 9,900	211	198	10	2	1
10,000- 24,000	313	301	8	1	3
25,000- 49,000	210	198	10	1	1
50,000- 99,000	120	112	4	1	3
100,000-490,000	53	51	1	1	0
500,000-990,000	18	18	0	0	0
≥1,000,000	17	16	0	1	0
Totals	1,281	1,204	52	10	15

[a] For plants examining only 100-ml portions of plant effluent, the percentage of positive 10-ml portions giving same MPN has been used.

6,400,000 per 100 ml. This occurred at plant 1. Monthly densities in excess of 1,000,000 per 100 ml were also recorded at two other plants. Each group is further subdivided according to the percentage of coliform positive portions found in the plant effluent during the month. Coliform bacteria were found during 7.6 percent of the months in which the raw water density was less than 10,000 per 100 ml; and during 6.2 percent of those in which the density was less than 100,000 per 100 ml.

Data for all 15 plant months in which the positive 10-ml portions equaled or exceeded 2 percent of those examined are given in table 13. Plants 8, 24, 44, and 53 again appear in this table. During October, 1954, the treated water produced at plant 44 showed 11.5 percent of all 10-ml portions examined to be positive for coliform bacteria. During May, 1953, plant 53 showed 9.7 percent of the treated water portions positive for coliform bac-

TABLE 13.—*Coliform bacterial data for raw and finished waters at conventional rapid sand filtration and disinfection water plants for all months during which 2.0 or more percent of the 10-ml portions of plant effluent examined were positive for coliform bacteria*

Plant code number	Year	Month	RAW WATER—Coliform density, monthly average MPN per 100 ml	PLANT EFFLUENT—10-ml portions: Number examined	PLANT EFFLUENT—10-ml portions: Percent positive
8	1954	June	[c]≧59,000	110	4.6
		Nov.	[c]≧99,000	100	3.0
24	1954	June	[c]57,000	150	3.3
		Sept.	[c]33,000	150	2.7
		Dec.	[c]18,000	155	3.2
44	1954	Feb.	[c]12,000	72	2.8
		Oct.	[c]10,000	78	11.5
53	1953	Jan.	[a]≧ 3,300	155	2.6
		Feb.	[a]± 430	140	2.1
		Mar.	[a]± 710	155	2.6
		May	[a]± 2,200	155	9.7
		Aug.	[a]± 670	155	2.6
	1954	Apr.	[a]± 1,500	150	3.3
		June	[a]≧ 4,600	150	2.0
		July	[a]≧ 8,800	155	3.2

[a] MPN by Thomas's approximate method. (10)
[c] Confirmed test.

teria. Both these plants carry low residual chlorine concentrations in the plant effluent.

Ten plants examined one or more 100-ml portions of plant effluent samples. The number and volumes of the portions examined, also the frequency with which samples were taken during the day, varied. The lower limits of detection of coliform bacteria ranged from 0.09 to 0.69 per 100 ml. As previously noted, when a plant examined two or more samples of finished water during the day, the results have been grouped and treated as a single sample.

In table 14, the sampling days are grouped according to the coliform bacterial density in the raw water. For each of these groups the frequency with which coliform bacteria were detected

TABLE 14.—*Effectiveness of conventional rapid sand filtration and disinfection water plants in the reduction of coliform bacteria at ten plants examining one or more 100-ML portions of plant effluent, daily data*

RAW WATER—Coliform density: Range, daily MPN per 100 ml	RAW WATER—Coliform density: Frequency, days	PLANT EFFLUENT—Days on which Coliform bacteria were detected[a]: Number	PLANT EFFLUENT—Days on which Coliform bacteria were detected[a]: Percent	PLANT EFFLUENT—Days on which Coliform density was >1.0 per 100 ml: Number	PLANT EFFLUENT—Days on which Coliform density was >1.0 per 100 ml: Percent
0- 4,900	2758	72	2.6	5	0.18
5,000- 9,900	640	33	5.2	2	.31
10,000- 24,000	1772	63	3.6	9	.51
25,000- 49,000	230	20	8.7	2	.87
50,000- 99,000	303	31	9.9	0	.00
100,000-240,000	465	26	5.6	0	.00
250,000-490,000	20	0	.0	0	.00
500,000-990,000	6	0	.0	0	.00
≧1,000,000	154	4	2.6	0	.00
Total or average	6348	249	3.9	18	.28

[a] Lower limits of coliform detection varied from 0.09 to 0.69 per 100 ml.

in the plant effluent, also the frequency with which the coliform density equaled or exceeded 1.0 per 100 ml, are given.

The maximum raw water loadings ranged from ⋝24,000 to ⋝23,000,000 per 100 ml. They exceeded 100,000 per 100 ml at 9 of the 10 plants. Coliform bacteria were detected in the plant effluent on 3.1 percent of the days during which the raw water loading was less than 10,000 per 100 ml, and on 3.8 percent of the days during which it was less than 100,000 per 100 ml. The maximum density of coliform bacteria detected in the finished water at any plant was 2.4 per 100 ml. The coliform bacterial density equaled or exceeded 1 per 100 ml in only 0.28 percent of the days on which finished water samples were examined.

Additional information on the relation of raw water bacterial loading to the occurrence and density of coliform bacteria in the plant effluent is given for each of these 10 plants in tables 15 to 24.

Table 25 summarizes coliform data for raw and finished water and residual chlorine concentration in finished water for each plant year. Those for the month of poorest bacterial quality of plant effluent are shown in table 26 and for the month of heaviest raw water coliform loading, in table 27.

TABLE 15.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 1*

RAW WATER—Coliform density[a]		PLANT EFFLUENT[b]			
		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml, for:	
Daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
⋜24	1	0	0	0	0
240	2	0	0	0	0
2400	14	0	0	0	0
24000	157	2	1.3	0.33	0.00
240000	164	2	1.2	1.85	.02
2400000	135	3	2.2	.40	.01
⋝23000000	15	1	6.7	.20	.01
Total or average	491	8	1.6	.72	.01

[a] Raw water samples examined by planting single portions in decimal volumes, presumptive test.
[b] Plant effluent samples examined using 551.0-ml. plantings, confirmed test.

TABLE 16.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 5*

RAW WATER		PLANT EFFLUENT[b]				
Coliform density[a]		Number of samples examined	Frequency of coliform-positive samples		Average coliform density MPN per 100 ml, for:	
Range, daily MPN per 100 ml	Frequency days		Number	Percent	Coliform-positive samples	All samples
0- 4,900...	14	42	0	0	0	0
5,000- 9,900...	36	108	1	0.9	0.68	0.006
10,000- 24,000...	156	468	0	0	0	0
25,000- 49,000...	82	246	[c]2	0.8	1.1	.009
50,000- 99,000...	141	423	1	0.2	1.1	.003
100,000-240,000...	57	171	1	0.6	.68	.004
250,000-490,000...	18	54	0	0	0	0
≥500,000........	6	18	0	0	0	0
No data...........	221	663	3	0.5	.81	0.004
Total or average...	731	2193	8	0.4	.89	0.003

[a] Raw water samples examined 5 days weekly by 0.442-ml plantings, confirmed test.
[b] Plant effluent samples examined every 8 hours by 151.0-ml plantings, completed test.
[c] Coliform bacteria detected in 100-ml portions of both 2 AM and 10 AM samples, July 28, 1953.

TABLE 17.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 12*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml, for:	
Range, daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
0- 4,900......	301	50	16.6	0.26	0.04
5,000- 9,900......	80	29	36.2	.25	.09
10,000- 24,000......	160	45	29.2	.20	.06
25,000- 49,000......	53	18	34.0	.30	.10
50,000- 99,000......	84	30	35.8	.14	.05
100,000-240,000......	51	20	39.3	.18	.07
240,000-490,000......	2	0	0	0	0
Total or average	731	102	26.3	0.22	0.06

[a] Raw water samples examined daily by planting 5 portions each of three decimal volumes directly into BGB lactose broth.
[b] Plant effluent sampled every 2 hours with 100-ml portion examined by confirmed test. For purposes of calculation the daily samples are considered as a single sample with twelve 100-ml portions examined.

TABLE 18.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 15*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml, for:	
Daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
≦24	54	1	1.9	0.22	0.00
≦240	13	2	15.4	.36	.06
240	91	6	6.6	.33	.02
2400	119	6	5.1	.22	.01
24000	91	10	11.0	.70	.08
≧24000	7	0	.0	.00	.00
≧240000	32	2	6.2	.36	.02
No data	223	7	3.1	.36	.01
Total or average	630	34	5.4	.47	.03

[a] Raw water samples examined by planting single portions of decimal volumes directly into BGB lactose broth.
[b] Plant effluent samples examined using five 100-ml plantings, confirmed test.

TABLE 19.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 17*

RAW WATER		PLANT EFFLUENT[b]		
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml
Range, daily MPN per 100 ml	Frequency days	Days	Percent	
0- 4,900	290	0	0	MPN of daily plant effluent samples all less than 0.22 per 100 ml
5,000- 9,900	143	0	0	
10,000- 24,000	194	0	0	
25,000- 49,000	0	0	0	
50,000- 99,000	61	0	0	
100,000-240,000	42	0	0	
250,000-490,000	0	0	0	
500,000-990,000	1	0	0	
Total or Avg.	731	0	0	

[a] Raw water samples examined daily by 2 plantings each of 3 decimal volumes, presumptive test.
[b] Plant effluent samples examined daily using five 100-ml portions, confirmed test.

Table 20.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 19*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml, for:	
Daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
≦23	2	0	0.00	0.00	0.00
230	8	0	.00	.00	.00
2400	313	2	.64	.22	.001
24000	359	2	.56	.22	.001
≧240000	48	1	2.10	.22	.004
Total or average	730	5	.68	.22	.001

[a] Raw water samples examined using 1,111-ml plantings, presumptive test.
[b] Plant effluent samples examined using five 100-ml planting, completed test.

Table 21.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 25*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml, for:	
Range, daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
0- 4,900	265	0	0	0	0
5,000- 9,900	142	0	0	0	0
10,000- 24,000	119	1	0.8	0.34	0.003
25,000- 49,000	71	0	0	0	0
50,000- 99,000	0	0	0	0	0
100,000-240,000	64	0	0	0	0
No data	69	0	0	0	0
Total or average	730	1	.2	.34	.001

[a] Raw water samples examined 6 or 7 days per week by 0.333-ml plantings, confirmed test.
[b] Filter effluent samples: once consisting of five 10-ml and three consisting of 100-ml portions each, examined daily. For mathematical averaging these four samples are treated as a single sample.

TABLE 22.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 35*

RAW WATER		PLANT EFFLUENT[b]		
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN per 100 ml
Daily MPN per 100 ml	Frequency days	Days	Percent	
230	7	0	0	MPN of daily plant effluent samples all <0.22 per 100 ml.
940	2	0	0	
2300	396	0	0	
9500	5	0	0	
24000	317	0	0	
≥240000	4	0	0	
Total or Avg.	731	0	0	

[a] Raw water samples examined daily by 0.111-ml plantings, presumptive test.
[b] Plant effluent samples examined daily using five 100-ml portions, confirmed test.

TABLE 23.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 38*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN/per 100 ml, for:	
Range daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
0- 4,900	345	3	0.9	1.1	0.01
5,000- 9,900	117	2	1.7	.9	.02
10,000- 24,000	120	3	2.5	1.1	.01
25,000- 49,000	24	1	4.2	1.1	.05
50,000- 99,000	17	0	0	0	0
100,000-240,000	3	0	0	0	0
Total or average	626	9	1.4	1.1	.02

[a] Raw water samples examined 6 days per week by 5.55-or 0.555-ml plantings, presumptive test.
[b] Plant effluent examined 6 days per week by 150-ml plantings, completed test.

TABLE 24.—*Relation of the occurrence and density of coliform bacteria in the plant effluent to the coliform density in the raw water, daily data, Plant No. 47*

RAW WATER		PLANT EFFLUENT[b]			
Coliform density[a]		Frequency of coliform-positive samples		Average coliform density, MPN/100 ml, for:	
Range daily MPN per 100 ml	Frequency, days	Days	Percent	Coliform-positive samples	All samples
0- 990	320	2	0.6	0.16	0.001
1,000- 4,900	201	0	0	0	0
5,000- 9,900	117	1	.9	.16	.001
10,000- 24,000	92	0	0	0	0
Total or average	730	3	.4	.16	.001

[a] Raw water samples examined daily by 55.5-ml plantings, confirmed test.
[b] Plant effluent data based on combined results of 3 samples—Plant No. 1, Plant No. 2, and Combined Plant Effluents—daily consisting of examinations of one, one, and five 100-ml plantings, completed test. For mathematical purposes these have been treated as one sample with seven 100-ml portions examined.

Table 25.—*Summary of coliform and residual chlorine data for conventional rapid sand filtration and disinfection water plants, annual data*

Plant code no.	Year	RAW WATER—Coliform density, annual average MPN per 100 ml	PLANT EFFLUENT: Coliform data, 100-ml portions: Number examined	100-ml portions: Percent positive	10-ml portions: Number examined	10-ml portions: Percent positive	Residual chlorine concentration, mg/l: Free: Annual average	Free: Minimum daily average	Total: Annual average	Total: Minimum daily average
1.........	1953	[p]≦1,700,000	1,280	0.55	1,290	0.00	...	...	[n]0.8	[n]0.1
	1954	[p]≦1,100,000	1,255	.80	1,255	.08	...	...	.6	.1
2.........	1955	[o]≦ 800,000	...	...	1,285	.00	...	...	.8	.2
3.........	1955	[p]≦ 510,000	...	...	1,715	.00	...	...	3.1	1.3
	1954	[p]≦ 450,000	...	...	1,650	.00	...	...	6.1	2.0
4.........	1953	[p]± 87,000	...	...	1,092	.00	...	...	[n].5	[n].5
	1954	[p]± 83,000	...	...	1,092	.00	...	...	[n].5	[n].3
5.........	1952	[o]± 75,000	1,098	.00	5,485	.04	.4	.00	[n]1.0	[n].3
	1953	[o]± 51,000	1,095	.27	5,485	.06	.1	.0	[n].8	[n].1
6.........	1954	[p]≦ 70,000	...	...	1,825	.00	.6	.3	...	
	1955	[p]± 65,000	...	...	1,825	.00	.8	.2	...	
7.........	1955	[p]± 68,000	...	...	1,820	.16	...	...	[n]2.0	[n]1.5
	1954	[p]± 39,000	...	...	1,825	.11	...	...	[n]2.0	[n]1.5
8.........	1954	[o]± 59,000	...	...	1,250	.72	...	...	.7	.1
	1953	[o]± 52,000	...	...	1,260	.00	...	...	.7	.1
9.........	1953	[p]≦ 55,000	...	...	1,365	.00	...	...	[n]2.2	[n]1.1
	1954	[p]≦ 40,000	...	...	1,350	.00	...	...	[n]2.3	[n]2.1
10.........	1955	[p]± 51,000	...	...	1,490	.00	...	...	[n]1.4	[n]1.0
	1954	[p]≦ 30,000	...	...	1,480	.00	...	...	[n]1.6	[n].9
11.........	1953	[p]± 49,000	...	...	1,820	.00	...	...	.4	.2
	1954	[p]± 42,000	...	...	1,660	.00	...	...	.4	.2
12.........	1951-52	[b]≦ 45,000	4,385	5.54	5,465	.00	...	...	[n]1.0	[n].9
	1952-53	[b]± 16,000	4,350	3.86	5,455	.00	...	...	[n]1.0	[n].7
13.........	1952	[o]≦ 44,000	...	...	1,565	.00	...	...	[n]1.7	[n]1.0
	1953	[o]± 23,000	...	...	1,280	.08	...	...	[n]1.7	[n]1.3
14.........	1954	[p]≦ 39,000	...	...	3,650	.00	...	...	.6	.3
	1953	[p]± 33,000	...	...	3,650	.00	...	...	.6	.4
15.........	1954	[b]± 39,000	1,565	2.68	...	...	...	...	[n].8	[n].7
	1953	[b]± 12,000	1,565	.96	...	...	...	...	[n].8	[n].6
16.........	1952	[p]≦ 38,000	...	...	7,300	.00	...	...	[n]0.7	[n]0.5
	1953	[p]≦ 7,800	...	...	7,260	.00	...	...	.7	.5
17.........	1952	[p]≦ 38,000	1,820	.00	...	...	...	...	1.3	0.9
	1953	[p]≦ 16,000	1,825	.00	...	...	...	...	1.3	1.0
18.........	1952	[p]≦ 37,000	...	...	7,290	.04	.3	.0	[n].6	[n].4
	1953	[p]≦ 17,000	...	...	7,275	.03	.5	.3	.7	.5
19.........	1955	[p]± 34,000	1,825	.16	...	...	...	...	[n]2.7	[n]2.2
	1954	[p]± 22,000	1,825	.11	...	...	...	...	[n]2.6	[n]2.1
20.........	1950	[p]≦ 33,000	...	...	1,825	.00	.8	.4	...	
	1949	[p]≦ 32,000	...	...	1,825	.00	.8	.5	...	

21........	1954	p ±	32,000	....	....	3,370	.00	....	....	.6	.4
	1953	p VII	27,000	....	....	3,350	.00	....	....	.5	.4
22........	1954	p ±	29,000	....	....	1,300	.00	....	....	[n].6	[n].4
	1953	p ±	26,000	....	....	1,545	.00	....	....	[n].7	[n].3
23........	1954	• VII	28,000	....	....	1,825	.00	.9	.7	....	
	1953	•	18,000	....	....	2,540	.00	1.0	.9	....	
24........	1954	•	28,000	....	....	1,825	.88	.8	.1	....	
	1953	• VII	23,000	....	....	1,825	.05	.8	.3	....	
25........	1953	p	28,000	1,095	.00	1,825	.00	....	....	1.2	.6
	1954	p	21,000	1,095	.09	1,825	.00	....	....	1.5	.8
26........	1953	p VII	28,000	....	....	1,825	.00	....	....	.4	.2
	1952	p ±	15,000	....	....	1,830	.00	....	....	.4	.2
27........	1953	• VII	25,000	....	....	1,585	.06	.3	.0	[n]1.0	[n].2
	1954	• VII	23,000	....	....	1,570	.00	.5	.0	[n]1.0	[n].6
28........	1953	p VII	23,000	....	....	1,535	.00	0.4	.2	....	
	1954	p VII	16,000	....	....	1,535	.00	0.4	.2	....	
29........	1954	pa VII	22,000	....	....	1,825	.00	....	....	[n].6	[n].2
	1953	pa VII	21,000	....	....	1,825	.00	....	....	[n].4	[n].2
30........	1954	p ±	19,000	....	....	1,540	.00	.5	.2	....	
	1955	p ±	15,000	....	....	1,465	.00	.5	.2	....	
31........	1954	p VII	19,000	....	....	1,825	.00	.0	.0	0.3	0.1
	1955	p VII	16,000	....	....	1,825	.00	.1	.0	.3	.1
32........	1951	p ±	17,000	....	....	1,482	.00	....	....	[n]1.4	[n].8
	1952	p	13,000	....	....	2,715	.00	....	....	[n]1.7	[n]1.3
33........	1955	• VII	17,000	....	....	3,110	.00	....	....	1.2	1.0
	1954	• VII	13,000	....	....	2,365	.00	....	....	1.5	1.0
34........	1952	p VII	16,000	....	....	2,745	.00	....	....	[n]1.8	[n]1.5
	1953	p	13,000	....	....	2,715	.00	....	....	[n]1.8	[n]1.1
35........	1952	p ±	13,000	1,830	0.00	....	....	....	....	.5	.3
	1953	p VII	12,000	1,825	.00	....	....	....	....	.5	.2
36........	1954	p	12,000	....	....	3,535	.03	....	....	[n]1.8	[n]1.3
	1953	p	9,000	....	....	3,475	.03	....	....	[n]1.6	[n].8
37........	1953	p ±	12,000	....	....	312	.0	....	....	[n].7	[n].2
	1954	p ±	11,000	....	....	311	.0	....	....	[n].8	[n].2
38........	1951	p	11,000	313	.6	1,565	.00	....	....	[n]1.5	[n].9
	1952	p ±	9,000	315	1.9	1,565	.06	....	....	[n]1.7	[n]1.0
39........	1953	p VII	10,000	....	....	900	.0	....	....	.4	.1
	1954	p VII	8,900	....	....	864	.0	....	....	.7	.2
40........	1953	p VII	9,800	....	....	1,825	.00	1.1	.5	1.6	.7
	1954	p VII	4,200	....	....	1,825	.00	1.6	.5	2.1	.8
41........	1954	p	8,800	....	....	5,475	.02	.1	(T)	[n].9	[n].4
	1953	p	6,900	....	....	5,475	.13	.1	(T)	[n].8	[n].4
42........	1953	b?	7,400	....	....	5,475	.00	....	....	.6	(T)
	1954	b?	6,300	....	....	5,475	.00	....	....	.6	(T)
43........	1952	p VII	7,000	....	....	3,660	.00	.2	(T)	.5	.4
	1953	p VII	6,600	....	....	3,650	.25	....	....	.5	.4
44........	1953	• ±	6,800	....	....	918	.2	....	....	.1	(T)
	1954	• ±	6,700	....	....	912	1.0	....	....	.1	.1
45........	1954	p VII	5,800	....	....	1,550	.00	.9	.2	....	
	1953	p VII	5,600	....	....	1,580	.00	1.2	.2	....	
46........	1955	• VII	5,100	....	....	1,825	.00	....	....	0.5	0.3
	1954	• VII	3,900	....	....	1,825	.11	....	....	.5	.3

TABLE 25.—*Summary of coliform and residual chlorine data for conventional rapid sand filtration and disinfection water plants, annual data—continued*

Plant code no.	Year	RAW WATER—Coliform density, annual average MPN per 100 ml	PLANT EFFLUENT							
			Coliform data				Residual chlorine concentration, mg/l			
			100-ml portions		10-ml portions		Free		Total	
			Number examined	Percent positive	Number examined	Percent positive	Annual average	Minimum daily average	Annual average	Minimum daily average
47	1954	[p] ≶ 5,000	2,555	0.08	......	......	0.1	(T)	.3	.1
	1955	[p] ≶ 4,000	2,555	.04	......	......	.1	(T)	.3	.1
48	1953	[c] ≶ 4,400	......	......	1,825	.06	......	......	[n].6	[n].3
	1954	[c] ≶ 2,400	......	......	1,825	.00	......	......	[n].6	[n].3
49	1954	[c] ± 4,100	......	......	1,815	.17	......	......	[n]1.1	[n].3
	1953	[c] ± 3,700	......	......	1,820	.11	......	......	[n].8	[n].4
50	1955	[c] ± 3,600	......	......	1,495	.00	......	......	[n]1.2	[n]1.0
	1954	[c] ± 2,900	......	......	1,670	.00	......	......	[n]1.3	[n]1.1
51	1953	[b] ± 3,500	......	......	7,280	.11	......	......	.4	.2
	1954	[b] ± 2,400	......	......	7,300	.01	......	......	.3	.2
52	1953	[p] ≶ 3,100	......	......	1,825	.00	......	......	[n].9	[n].6
	1954	[p] ≶ 3,000	......	......	1,825	.00	......	......	[n].9	[n].6
53	1954	[pa] ± 2,400	......	......	1,825	.93	......	......	.1	(T)
	1953	[pa] ± 1,100	......	......	1,825	1.75	......	......	.1	(T)
54	1952	[c] ± 1,900	......	......	1,825	.00	.6	.4	.8	.5
	1953	[c] ± 1,300	......	......	1,815	.00	6	.4	.8	.5

[a] MPN by Thomas's approximate formula
[b] direct planting into BGB lactose broth
[c] confirmed test
[n] ammonia added
[p] presumptive test

TABLE 26.—*Summary of coliform and residual chlorine data for months of poorest effluents at the conventional rapid sand filtration and disinfection water plants*

Plant code no.	Year	Month	RAW WATER—Coliform density, monthly average MPN per 100 ml	PLANT EFFLUENT: Coliform data: 100-ml portions: Number examined	PLANT EFFLUENT: Coliform data: 100-ml portions: Percent positive	PLANT EFFLUENT: Coliform data: 10-ml portions: Number examined	PLANT EFFLUENT: Coliform data: 10-ml portions: Percent positive	Residual chlorine concentration, mg/l: Free: Monthly average	Residual chlorine concentration, mg/l: Free: Minimum daily average	Residual chlorine concentration, mg/l: Total: Monthly average	Residual chlorine concentration, mg/l: Total: Minimum daily average
1	1953	Aug.	[p]≧2,300,000	105	4.8	105	0.0	...	...	[n]0.7	[n]0.1
	1954	Nov.	[p] 1,100,000	105	0.0	165	1.0	...	...	.9	0.6
2	1955	...	...	...	...	...	...	...	...	...	
3	1955	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
4	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
5	1952	Mar.	[a] 52,000	92	1.1	460	.4	0.2	0.0	[n]1.1	[n]0.7
	1953	July	[a] 75,000	93	2.2	465	.2	.1	.0	[n].8	[n].6
6	1954	...	...	...	...	...	...	...	...	...	
	1955	...	...	...	...	...	...	...	...	...	
7	1955	July	[p]≧ 140,000	...	...	155	1.9	...	...	[n]2.0	[n]2.0
	1954	Mar.	[p] 8,500	...	...	155	1.3	...	...	[n]2.0	[n]2.0
8	1954	June	[a]≧ 59,000	...	...	110	4.5	...	...	.4	0.2
	1953	...	...	...	...	...	...	...	...	...	
9	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
10	1955	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
11	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
12	1951-52	Jan.	[b] 7,700	370	20.0	465	.0	...	...	[n]1.0	[n]0.9
	1952-53	Dec.	[b]≧ 4,600	372	16.4	460	.0	...	...	[n]1.0	[n]1.0
13	1952	...	...	...	...	...	...	...	...	...	
	1953	Aug.	[a]≧ 31,000	...	...	120	.8	...	...	2.9	2.7
14	1954	...	...	...	...	...	...	...	...	...	
	1953	...	...	...	...	...	...	...	...	...	
15	1954	Oct.	[b]≧ 90,000	130	11.5	...	...	...	...	[n].8	[n].7
	1953	Aug.	[b]≧ 5,100	130	9.2	...	...	...	...	[n].8	[n].8
16	1952	...	...	...	...	...	...	...	...	...	
	1953	...	...	...	...	...	...	...	...	...	
17	1952	...	...	...	...	...	...	...	...	...	
	1953	...	...	...	...	...	...	...	...	...	
18	1952	Sept.	[p] 21,000	...	...	595	0.2	0.2	0.0	[n]0.6	[n]0.5
	1953	Apr.	[p] 5,400	...	...	600	.2	.6	.5	0.7	.6
19	1955	Oct.	[p]≧ 48,000	...	...	155	1.9	...	...	[n]2.8	[n]2.2
	1954	Feb.	[p]≧ 19,000	...	...	140	.7	...	...	[n]2.4	[n]2.1

TABLE 26.—*Summary of coliform and residual chlorine data for months of poorest effluents at the conventional rapid sand filtration and disinfection water plants*—Continued

Plant code no.	Year	Month	RAW WATER Coliform density, monthly average MPN per 100 ml	PLANT EFFLUENT: Coliform data: 100-ml portions: Number examined	PLANT EFFLUENT: Coliform data: 100-ml portions: Percent position	PLANT EFFLUENT: Coliform data: 10-ml portions: Number examined	PLANT EFFLUENT: Coliform data: 10-ml portions: Percent position	PLANT EFFLUENT: Residual chlorine concentration, mg/l: Free: Monthly average	PLANT EFFLUENT: Residual chlorine concentration, mg/l: Free: Minimum daily average	PLANT EFFLUENT: Residual chlorine concentration, mg/l: Total: Monthly average	PLANT EFFLUENT: Residual chlorine concentration, mg/l: Total: Minimum daily average
20	1950										
	1949										
21	1954										
	1953										
22	1954										
	1953										
23	1954										
	1953										
24	1954	June	[a] 57,000			150	3.3	1.0	.6		
	1953	Mar.	[a] 15,000			155	.6	.7	.5		
25	1953										
	1954	June	[b] 11,000	90	1.1	150	.0			1.1	.9
26	1953										
	1952										
27	1953	Feb.	[a] ≦ 37,000			135	.7	.0	.0	[n]1.0	[n].4
	1954										
28	1953										
	1954										
29	1954										
	1953										
30	1954										
	1955										
31	1954										
	1955										
32	1951										
	1952										
33	1955										
	1954										
34	1952										
	1953										
35	1952										
	1953										
36	1954	July	[b] 14,000			305	0.3			[n]1.9	[n]1.7
	1953	Aug.	[b] 8,800			310	.3			[n]1.7	[n]1.4
37	1953										
	1954										
38	1951	Sept.	[b] 14,200	25	4.0	125	.0			[n]1.5	[n]1.1
	1952	Oct.	[b] 4,100	27	7.4	135	.7			[n]2.1	[n]1.1

39	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
40	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
41	1954	Feb.	[p] 27,000	...	...	420	.02	(T)	(T)	[n].8	[n].6
	1953	Jan.	[p] 14,000	...	...	465	.06	0.1	(T)	[n]1.1	[n]0.8
42	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
43	1952	...	...	...	...	...	...	...	...	...	
	1953	Dec.	[p] 1,600	...	...	310	1.3	...	...	.5	.4
44	1953	Jan.	[c] ± 10,000	...	...	75	4.0	...	...	.2	.2
	1954	Oct.	[c] ± 10,000	...	...	78	11.5	...	...	.1	.1
45	1954	...	...	...	...	...	...	...	...	...	
	1953	...	...	...	...	...	...	...	...	...	
46	1955	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
47	1954	Aug.	[p] ≥ 3,100	...	...	217	0.9	0.1	(T)	0.3	0.1
	1955	Sept.	[p] ≥ 3,500	...	...	310	.5	.1	(T)	.3	.2
48	1953	Sept.	[c] 60	...	...	155	.6	...	...	[n].6	[n].5
	1954	...	...	...	...	...	...	...	...	...	
49	1954	Dec.	[c] ≥ 14,000	...	...	150	1.3	...	...	[n].8	[n].5
	1953	May	[c] 4,800	...	...	155	1.3	...	...	.9	.6
50	1955	...	...	...	...	...	...	...	...	...	...
	1954	...	...	...	...	...	...	...	...	...	
51	1953	July	[b] ≥ 9,500	...	...	620	.5	...	...	.4	.3
	1954	July	[b] ≥ 1,500	...	...	630	.2	...	...	.3	.2
52	1953	...	...	...	...	...	...	...	...	...	
	1954	...	...	...	...	...	...	...	...	...	
53	1954	Apr.	[pa] ± 1,800	...	...	150	3.3	...	...	.1	.1
	1953	May	[pa] ≥ 2,200	...	...	155	9.7	...	...	.2	.1
54	1952	...	...	...	...	...	...	...	...	...	
	1953	...	...	...	...	...	...	...	...	...	

[a] MPN by Thomas's approximate formula
[b] direct planting into BGB lactose broth
[c] confirmed test
[n] ammonia added
[p] presumptive test

TABLE 27.—*Summary of coliform and residual chlorine data for months of greatest bacterial loadings of raw waters at the conventional rapid sand filtration and disinfection water plants*

Plant code no.	Year	Month	RAW WATER—Coliform density, monthly average MPN per 100 ml	PLANT EFFLUENT — Coliform data — 100-ml portions: Number examined	100-ml portions: Percent positive	10-ml portions: Number examined	10-ml portions: Percent positive	Residual chlorine concentration, mg/l — Free: Monthly average	Free: Minimum daily average	Total: Monthly average	Total: Minimum daily average
1	1953	Sept.	[p] ≥6,400,000	105	1.0	105	0.0	...	...	[n] 0.7	[n] 0.3
	1954	Oct.	[p] ≥2,300,000	105	.0	105	.0	...	...	.6	.3
2	1955	Oct.	[e] ≥2,400,000	...	...	120	.0	...	...	.8	.2
3	1955	Sept.	[p] ≥1,100,000	...	...	140	.0	...	...	3.3	2.1
	1954	May	[p] ≥700,000	...	...	130	.0	...	...	6.5	3.5
4	1953	May	[p] ≥160,000	...	...	93	.0	...	...	[n] .5	[n] .5
	1954	Dec.	[p] ≥160,000	...	...	93	.0	...	...	[n] .3	[n] .3
5	1952	Nov.	[e] ≥160,000	89	.0	450	.0	0.2	0.0	[n] .9	[n] .4
	1953	Dec.	[e] 82,000	93	.0	465	.0	.0	.0	[n] 1.0	[n] .8
6	1954	Aug.	[p] ≥110,000	...	...	155	.0	.6	.4	...	
	1955	Oct.	[p] ≥91,000	...	...	155	.0	.5	.3	...	
7	1955	Sept.	[p] 280,000	...	...	150	.0	...	...	[n] 2.0	[n] 2.0
	1954	Sept.	[p] ≥190,000	...	...	150	.0	...	...	[n] 2.0	[n] 2.0
8	1954	Aug.	[e] ≥100,000	...	...	110	.0	...	...	.7	.5
	1953	Nov.	[p] ≥80,000	...	...	90	.0	...	...	.7	.1
9	1953	Oct.	[p] ≥100,000	...	...	100	.0	...	...	[n] 2.2	[n] 2.2
	1954	Aug.	[p] ≥99,000	...	...	120	.0	...	...	[n] 2.4	[n] 2.2
10	1955	Sept.	[p] ≥110,000	...	...	120	.0	...	...	1.5	1.0
	1954	Jan.	[p] ≥65,000	...	...	125	.0	...	...	1.6	1.3
11	1953	June	[p] ±99,000	...	...	145	.0	...	...	.3	.2
	1954	Oct.	[p] ±73,000	...	...	155	.0	...	...	.4	.3
12	1951-52	Sept.	[b] ≥110,000	360	.8	450	.0	...	...	[n] 1.0	[n] .9
	1952-53	Feb.	[b] ≥48,000	360	4.4	450	.0	...	...	[n] 1.0	[n] .8
13	1952	Apr.	[e] ≥95,000	...	...	140	.0	...	...	[n] 1.7	[n] 1.0
	1953	July	[e] ≥58,000	...	...	95	.0	...	...	[n] 3.0	[n] 2.5
14	1954	Feb.	[p] ≥65,000	...	...	280	.0	...	...	.6	.5
	1953	Mar.	[p] ≥56,000	...	...	310	.0	...	...	.5	.4
15	1954	June	[b] ≥110,000	130	3.8	...	...	...	...	[n] .9	[n] .7
	1953	June	[b] ≥36,000	130	.0	...	...	...	...	[n] .8	[n] .6
16	1952	Aug.	[p] 130,000	...	...	615	0.0	...	...	[n] 0.8	[n] 0.7
	1953	Sept.	[p] ≥22,000	...	...	600	.0	...	...	.8	0.7
17	1952	June	[p] ≥130,000	150	0.0	...	...	...	...	1.2	1.0
	1953	July	[p] ≥49,000	155	.0	...	...	...	...	1.4	1.3
18	1952	Jan.	[p] ≥120,000	...	...	615	.0	0.4	0.4	.6	0.5
	1953	Mar.	[p] 36,000	...	...	620	.0	.4	.3	.6	.6
19	1955	Aug.	[p] ≥69,000	...	...	155	.0	...	...	2.5	[n] 2.2
	1954	Sept.	[p] ≥60,000	...	...	150	.0	...	...	2.7	[n] 2.3

20	1950	July	[p] [VII] 58,000			155	.0	.7	.5		
	1949	Aug.	[p] [VII] 59,000			155	.0	.6	.6		
21	1954	Dec.	[p] [VII] 49,000			285	.0			.5	.4
	1953	Mar.	[p] [VII] 60,000			285	.0			.5	.5
22	1954	July	[p] [VII] 86,000			110	.0			[n].5	[n].4
	1953	July	[p] [VII] 57,000			135	.0			[n].6	[n].4
23	1954	Apr.	• 70,000			150	.0	1.0	1.0		
	1953	May	• 36,000			270	.0	1.0	1.0		
24	1954	June	• 57,000			150	3.3	1.0	.6		
	1953	June	• 43,000			150	.0	.9	.7		
25	1953	Nov.	[p] 95,000	90	.0	150	.0			1.2	.7
	1954	Sept.	[p] 70,000	90	.0	150	.0			1.2	1.2
26	1953	Sept.	[p] [VII] 56,000			150	.0			.4	.3
	1952	July	[p] [±] 42,000			155	.6			.5	.4
27	1953	June	[e] [VII] 78,000			130	.0	.1	T	[n].9	[n].8
	1954	June	[e] [VII] 79,000			130	.0	.1	.0	[n]1.0	[n].8
28	1953	Dec.	[p] [VII] 51,000			130	.0	.4	.2		
	1954	Oct.	[p] [VII] 30,000			130	.0	.4	.3		
29	1954	Jan.	[p] [VII] 40,000			155	.0			[n].4	[n].4
	1953	Jan.	[p] [VII] 34,000			155	.0			.6	.5
30	1954	Oct.	[p] [VII] 46,000			135	.0	.4	.3		
	1955	Jan.	[p] [VII] 24,000			125	.0	.5	.4		
31	1954	Aug.	[p] [VII] 28,000			155	0.0	0.0	.1	.1	.1
	1955	June	[p] [VII] 32,000			150	.0	.0	.0	.3	.3
32	1951	June	[p] [VII] 38,000			130	.0			[n]1.2	[n].9
	1952	July	[p] [VII] 31,000			130	.0			[n]1.7	[n]1.5
33	1955	Aug.	[e] [VII] 58,000			300	.0			1.5	1.5
	1954	May	[e] [VII] 48,000			150	.0			1.4	1.1
34	1952	Nov.	[p] [VII] 32,000			195	.0			[n]1.8	[n]1.7
	1953	June	[p] 25,000			240	.0			[n]1.6	[n]1.1
35	1952	June	[p] [VII] 28,000	150	.0					.4	.3
	1953	Sept.	[p] 18,000	150	.0					.5	.4
36	1954	June	[p] 25,000			290	.0			[n]1.8	[n]1.4
	1953	June	[p] 20,000			195	.0			[n]1.7	[n]1.4
37	1953	May	[p] [±] 32,000			27	.0			[n].7	[n].5
	1954	Dec.	[p] [VII] 45,000			27	.0			.6	.2
38	1951	June	[p] 31,000	25	4.0	125	.0			[n]1.5	[n]1.0
	1952	Nov.	[p] [±] 21,000	25	.0	125	.0			[n]2.2	[n]1.6
39	1953	June	[p] [VII] 29,000			81	.0			.5	.1
	1954	July	[p] [VII] 44,000			78	.0			.3	.1
40	1953	June	[p] [VII] 33,000			150	.0	.9	.7	1.2	.9
	1954	June	[p] [VII] 9,300			150	.0	1.3	.5	1.8	.8
41	1954	Feb.	[p] 27,000			420	.2	(T)	(T)	[n].8	[n].6
	1953	Feb.	[p] 26,000			420	.2	.1	(T)	[n]1.0	[n].6
42	1953	May	[b] [VII] 25,000			465	.0			.5	.4
	1954	Nov.	[b] 14,000			450	.0			.5	.4
43	1952	June	[p] [VII] 14,000			300	.0	.3	.2	.5	.4
	1953	Aug.	[p] [VII] 12,000			310	.0			.5	.3
44	1953	Dec.	[e] [±] 14,000			78	.0			.1	.1
	1954	April	[e] [±] 10,000			78	.0			.2	.2
45	1954	Dec.	[p] [VII] 24,000			155	.0	1.3	.8		
	1953	Jan.	[p] [VII] 15,000			130	.0	1.8	1.4		

TABLE 27.—*Summary of coliform and residual chlorine data for months of greatest bacterial loadings of raw waters at the conventional rapid sand filtration and disinfection water plants*—Continued

Plant code no.	Year	Month	RAW WATER—Coliform density, monthly average MPN per 100 ml	PLANT EFFLUENT							
				Coliform data				Residual chlorine concentration, mg/l			
				100-ml portions		10-ml portions		Free		Total	
				Number examined	Percent positive	Number examined	Percent positive	Monthly average	Minimum daily average	Monthly average	Minimum daily average
46	1955	Mar.	[c] ≤ 9,900	....	....	155	.0	....	....	.5	.4
	1954	Oct.	[c] ≤ 7,000	....	....	155	.0	....	....	.6	.5
47	1954	Oct.	[p] ≤ 9,500	....	....	217	.0	.2	(T)	.4	.2
	1955	Nov.	[p] ≤ 7,700	....	....	210	.0	.1	(T)	.3	.2
48	1953	June	[c] ≤ 9,100	....	....	150	.0	....	....	[n].5	[n].4
	1954	May	[c] ≤ 7,100	....	....	155	.0	....	....	[n].5	[n].4
49	1954	Dec.	[c] ≤ 14,000	....	....	150	1.3	....	....	[n].8	[n].5
	1953	Mar.	[c] 12,000	....	....	155	.0	....	....	[n].7	[n].5
50	1955	July	[c] ≤ 7,600	....	....	150	.0	....	....	[n]1.1	[n]1.0
	1954	Oct.	[c] ≤ 11,000	....	....	155	.0	....	....	[n]1.2	[n]1.2
51	1953	Jan.	[b] ≤ 11,000	....	....	620	.0	....	....	.4	.3
	1954	Sept.	[b] ≤ 12,000	....	....	600	.0	....	....	.4	.3
52	1953	May	[p] ≤ 8,200	....	....	155	.0	....	....	[n].8	[n].7
	1954	Oct.	[p] ≤ 8,900	....	....	155	.0	....	....	[n].9	[n].8
53	1954	July	[pa] ≤ 8,800	....	....	155	3.2	....	....	.1	.1
	1953	Jan.	[pa] ≤ 3,300	....	....	155	2.6	....	....	.1	.1
54	1952	Jan.	[c] ≤ 6,500	....	....	155	.0	.7	.5	.8	.7
	1953	Jan.	[c] ≤ 4,500	....	....	155	.0	.7	.6	.8	.7

[a] MPN by Thomas's approximate formula
[b] direct planting into BGB lactose broth
[c] confirmed test
[n] ammonia added
[p] presumptive test

Conclusions

Data from 54 plants treating waters with monthly average coliform densities frequently in excess of 5,000 per 10 ml have been analyzed. Conventional rapid sand filtration plants providing continuous and adequate disinfection can treat waters heavily laden with coliform bacteria to produce a plant effluent conforming to the assumed bacteriological objective. Increased chlorine applications have made this possible.

The number of 10-ml portions of plant effluent which were found positive for coliform bacteria equaled or exceeded 2 percent of those planted during only 1.2 percent of 1,281 plant months of record. All of these months occurred at four plants. Two of the plants maintained total chlorine residuals in the finished water averaging only 0.1 mg/l. At each of the other plants the pretreated and filtered water was subject to air- and bird-borne contamination. Water treatment plants which have adequate and properly operated facilities can and should produce an effluent which does not have more than 2 percent of all 10-ml portions examined during any one month positive for coliform bacteria. This is the assumed bacteriological objective applicable only to plant effluent samples. Evaluation of the bacterial quality of the water actually furnished to the consumers should still be based on the *Public Health Service Drinking Water Standards.*

PREDISINFECTION, COAGULATION, AND SEDIMENTATION

Plants Studied

All data sufficient for study of the effectiveness of predisinfection, coagulation, and settling as measured by the removal of coliform bacteria have been examined. Data from 19 plants, including plants 33a and 33b, which were operated in parallel, have been summarized. Data for plant 18b, where prechlorination was frequently inadequate to maintain a residual in the settled effluent, is discussed separately.

There are wide variations in the treatment provided at the different plants, and in some cases considerable variation during the two-year period at a given plant. Six of the 19 plants routinely used chloramine for predisinfection; the others normally used chlorine only. Average chlorine dosages ranged from 1.3 to 14.0 mg/l. Median values for plants using chlorine and chloramine were 3.6 and 1.5 mg/l, respectively. Theoretical contact times ranged from slightly less than 2 to more than 100 hours. The median times for both chlorine and chloramine were 12 hours. The average total residual chlorine in the water applied to the filters ranged from 0.2 to 5.9 mg/l and the medians were 0.8 mg/l for both predisinfection processes. Several plants recorded total residual chlorine concentrations of 0.0 mg/l in the influent to filter for 1 or more months. It may also be significant that the median pH at plants using chloramine was 9.2, while that for plants using chlorine was 8.0.

Discussion

All available bacteriological data, except those for Plant 18b, are summarized in table 28. Those for the predisinfected, coagulated, and settled water samples have been classified according to

TABLE 28.—*Effectiveness of predisinfection, coagulation and sedimentation in the reduction of coliform bacteria, monthly data*

RAW WATER—Coliform density		INFLUENT TO FILTER—Percentage of months during which the percentage of Coliform-positive 10-ml portions was—			
Range, monthly average MPN per 100 ml	Frequency, months	0.0	0.1-1.9	2.0-9.9	≥10
Thirteen Plants Disinfecting by Prechlorination					
0- 4900	64	89.0	9.3	1.7	0.0
5000- 9900	36	94.4	5.6	0.0	.0
10000- 24000	52	84.6	9.6	5.8	.0
25000- 49000	48	85.4	12.5	2.1	.0
50000- 99000	35	77.2	8.6	14.2	.0
100000-240000	6	83.3	.0	16.7	.0
250000-490000	20	100.	.0	.0	.0
500000-990000	13	100.	.0	.0	.0
≥1000000	14	86.6	.0	7.2	7.2
Total or Average	288	87.8	7.6	4.2	.4
Six plants using prechloramine disinfection					
0- 4900	45	60.0	20.0	17.8	2.2
5000- 9900	31	80.7	12.9	6.4	.0
10000- 24000	43	65.2	11.6	20.9	2.3
25000- 49000	16	81.3	12.5	6.2	.0
50000- 99000	6	50.0	33.3	16.7	.0
100000-240000	2	100.0	0.0	0.0	.9
250000-490000	1	100.0	0.0	0.0	.0
Total or Average	144	68.8	15.2	14.6	1.4

the percentage of 10-ml portions testing positive for coliform bacteria. For the 432 plant months examined, there were 36 months during which the percentage of coliform positive portions exceeded 2 percent of all those examined, and 3 months during which they exceeded 10 percent of those examined.

The comparison of the frequencies of the various percentages of positive portions in the settled water samples disinfected with chlorine and chloramine is interesting. Although this points to the relative ineffectiveness of the disinfecting properties of chloramine as compared to those of chlorine, other factors were involved. It should be remembered that it was not the objective of those in charge of plant operation to provide a coliform-bacteria-free water for application to the filter, and in many cases a substantial combined chlorine residual was maintained throughout the settling basins even though a relatively low level of chloramine had been applied.

Data from Plant 18b gave non-typical results (table 29) due

TABLE 29.—*Effect of increased residual chlorine concentration on the detection of coliform bacteria in predisinfected, coagulated and settled water, monthly data, Plant No. 18b*

Year and month	RAW WATER—Coliform density monthly average MPN per 100 ml	INFLUENT TO FILTER			
		10-ml portions examined for coliform bacteria		Residual chlorine concentration, mg/l	
		Number	Percent positive	Monthly average	Minimum daily average
1952					
Jan.	>116000	130	7	0.06	0.02
Feb.	29000	125	1	.03	.01
Mar.	47000	130	0	.02	.00
Apr.	63000	130	16	.00	.00
May	13000	130	25	.13	.00[a]
June	13000	125	12	.05	.00[a]
July	> 36000	130	15	.01	.00[a]
Aug.	28000	130	12	.04	.00[a]
Sept.	21000	125	41	.01	.00[a]
Oct.	8400	110	89	.00	.00
Nov.	> 22000	120	63	.05	.00
Dec.	40000	130	12	.10	.02
Total or Average	37000	1515	23	.04	....
1953					
Jan.	40000	130	13	0.04	0.00
Feb.	23000	120	6	.01	.00
Mar.	36000	130	2	.01	.00
Apr.	5400	130	11	.01	.00
May	6600	125	18	.50	.00
June	11000	130	5	.71	.56
July	24000	130	5	.74	.54
Aug.	> 32000	130	0	.76	.55
Sept.	11000	125	0	.83	.62
Oct.	5200	135	0	.72	.52
Nov.	3400	120	1	.79	.47
Dec.	5000	125	0	.85	.13
Total or Average	17000	1530	5	....	....

[a] Prechloramine disinfection used May 15 to September 8, 1952.

to depletion of the chlorine or chloramine in the large open earthen settling tanks which provided theoretical detention times around 35 to 40 hours. Daily combined chlorine residuals were frequently recorded as 0.00 and monthly averages ranged from 0.00 to 0.13 mg/l throughout 1952, during which 23 percent of all 10-ml portions, and 5.5 percent of all 1.0-ml portions of settled water examined were positive for coliform bacteria by confirmed test. Better disinfection was secured during the last 6 months of 1953 when total residual chlorine concentrations in the settled water were maintained between 0.1 and 1.3 mg/l, with monthly averages around 0.8. During this period only 1.0 percent of the 10-ml portions, and 0 percent of all 1-ml portions examined were found positive for coliform bacteria. Data from Plant 18a, which operates in parallel with 18b, but prechlorinated to provide a monthly average residual of 0.6 to 0.7 mg/l after 2 to 3 hours theoretical detention, show less than 0.7 percent of all 10-ml portions of settled water examined during a two-year period to be positive for coliform bacteria.

Conclusion

Prechlorination, coagulation, and sedimentation are more effective than coagulation, sedimentation, and rapid sand filtration in the reduction of coliform bacteria. Data from 19 plants indicate that much of the time prechlorination, coagulation, and sedimentation can produce water conforming to the assumed bacteriological objective. Effective bacterial reduction is largely dependent upon the maintenance of substantial chlorine residuals throughout the coagulation and sedimentation basins.

Coliform bacteria embedded in particulate matter may survive. One plant operator reported that he consistently found coliform bacteria in the scum at the outlet end of settling basins.

As practiced at the plants studied, predisinfection using chloramine was less effective than at plants using chlorine only.

Predisinfection, coagulation, and sedimentation are commonly used as pretreatment to filtration. They alone should not be considered adequate treatment for raw waters subject to any appreciable contamination.

COAGULATION, SEDIMENTATION, AND FILTRATION

Data from only 6 of the 54 plants could be used to study the efficiency of coagulation, sedimentation, and filtration as measured by removal of coliform bacteria. Three plants (Nos. 26, 35, and 53) routinely used postdisinfection only. Records for 3 other plants (Nos. 29, 43, and 48) permitted a study of the effect of discontinuance of prechlorination. All the remaining plants applied chlorine, or chloramine, prior to filtration.

Presentation of Data

Plant 26 was constructed during 1950. Normal treatment consisted of the addition of alum (31 mg/l)[a] and lime (11 mg/l), followed by mixing and flocculation accomplished by tangential-inflow into a circular tank (1 hour), sedimentation (12 hours), and filtration (2.0 gpm/sq. ft.). Postdisinfection completed the treatment.

[a] Values given in parenthesis are average data (chemical dosage, theoretical detention time, or rate of filtration) for the two-year period.

The bacteriological data for raw and filtered waters are shown in tables 30 and 31. In table 30 these data are first grouped ac-

TABLE 30.—*Effectiveness of coagulation, sedimentation and filtration in the reduction of coliform bacteria, daily data, plant no. 26*

RAW WATER—Coliform Density[a]		FILTER EFFLUENT[b]			
Daily, MPN per 100 ml	Frequency, days	Frequency with which 1-ml portions were coliform-positive: Days	Frequency with which 1-ml portions were coliform-positive: Percent	Coliform density, average MPN/100ml	Effectivness in reduction of coliform bacteria, percent
≦230	5	2	40	[c]52	≦77.4
2300	388	177	46	[c]61	97.3
(2100)[d]	....	....	....	[d]70	[d]96.7
9500	1	1	....	[c]≧230	....
24000	307	161	53	[c]75	99.7
(22000)[d]	....	....	....	[d]84	[d]99.6
≧240000	30	15	50	[c]70	≧99.9
Total or ≐ 21,200 Average (7000)[d]	731	356	49	≧ [c]67 [d]77	≦99.7 [d]98.9

[a] Raw water samples examined daily by 0.111-ml plantings, presumptive test.
[b] Filter effluent samples examined daily using one 1-ml. planting, confirmed test.
[c] Estimated MPN per 100 ml $= 280 \log_{10} \left(\frac{\text{Portions planted}}{\text{Portions negative}}\right)$

[d] Estimated MPN obtained by assuming the results from each 10 consecutive daily samples for raw water loading under consideration to be those from a single sample and applying Thomas's (12) log-probability procedure.

cording to the daily raw water coliform bacterial density. Then the frequencies with which 1-ml portions of filter effluent were positive for coliform bacteria are given for each raw water loading. The average MPN's per 100 ml for filter effluents have been estimated (1) by assuming all data for each group to be the result of a single sample, and (2) by Thomas's (12) log-probability procedure. In applying Thomas's procedure the results from each 10 consecutive daily samples for the raw water loading under consideration have been assumed to be those from a single sample. Indicated efficiencies are given for the various raw water loadings.

Table 31 summarizes the average monthly data for the 2-year period studied.

Plant 35 treated water from the same river intake and in essentially the same manner as Plant 26. Average treatment was as follows: Approximately two-thirds of the water was presettled (6 hours), all of it was then treated with alum (39 mg/l) and lime (14 mg/l), after which it was mixed (10 minutes) and settled (10 hours) in plain basins. From these it flowed through any 1 of 4 types of rapid sand filters, ranging from converted pressure filters to units of modern design. All filters discharged to a common clear well. In flowing to a second clear well, the water was disinfected with chlorine or chloramine.

Coliform bacterial data for raw and combined filter effluent water samples are given in table 32. Although the filter effluent

TABLE 31.—*Effectiveness of coagulation, sedimentation and filtration in the reduction of coliform bacteria, monthly data, plant no. 26*

Year and month	RAW WATER—Coliform density,[a] monthly average MPN per 100 ml	FILTER EFFLUENT[b] — 1-ml portions examined for coliform bacteria: Number	FILTER EFFLUENT[b] — 1-ml portions examined for coliform bacteria: Per Cent positive	FILTER EFFLUENT[b] — Coliform density,[c] monthly average MPN/100 ml	Effectiveness in reduction of coliform bacteria, percent
1952					
January	7900	31	20	104	98.7
February	≥ 5200	29	13	60	98.8
March	≥ 4300	31	14	61	98.6
April	8800	30	9	36	99.6
May	9300	31	26	183	98.0
June	≥18900	30	12	51	99.7
July	≈41700	31	18	87	99.8
August	10700	31	24	149	98.6
September	≥22500	30	21	120	99.5
October	≥20500	31	16	73	99.6
November	≥18900	30	12	51	99.7
December	10000	31	15	67	99.3
Year	≈14900	366	200	81	99.4
1953					
January	12100	31	18	87	99.3
February	≥17500	28	13	63	99.6
March	9500	31	7	26	99.7
April	≥18900	30	8	31	99.8
May	≥17700	31	6	22	99.9
June	≥29700	30	14	63	99.2
July	≥22600	31	8	30	99.9
August	≥34400	31	10	40	99.9
September	≥55700	30	14	63	99.9
October	≥55300	31	23	136	99.8
November	≥33300	30	14	63	99.8
December	≥23300	31	21	113	99.5
Year	≥27600	365	156	56	99.8

[a] Raw water samples examined daily using 0.111-ml plantings, presumptive test.
[b] Filter effluent samples examined daily using one 1-ml planting, confirmed test.
[c] Estimated MPN per 100 ml = 230 $\log_{10}\left(\frac{\text{Portions planted}}{\text{Portions negative}}\right)$

data are for presumptive test only, the comparison of presumptive and confirmed test data for the filter effluent of Plant 26, which treated the same raw water, indicates that approximately 100 percent of all these presumptive positives would also show presence of coliform bacteria by the confirmed test.

Plant 53 is a purification and softening plant. It is in the large plant classification. Average treatment consisted of the addition of alum (30 mg/l), lime (169 mg/l), and soda-ash (75 mg/l), followed by rapid mixing, flocculation (50 minutes) and settling (2 hours), recarbonation and resettling (6 hours), and then filtration at rates ranging from 1.6 to 3.0 gpm/sq. ft. Disinfection was by marginal postchlorination (0.3 mg/l), which provided total chlorine residuals ranging from less than 0.05 to 0.3 mg/l after 5 to 10 hours theoretical contact time. The pH of the filtered water varied from 9.1 to 10.9 and averaged 10.3.

Table 33 summarizes the coliform bacterial data for raw and filtered waters.

Plant 29 treated water with alum (37 mg/l), usually carbon (1.6 mg/l), and part time predisinfection with chlorine (1.2

TABLE 32.—*Effectiveness of coagulation, sedimentation and filtration in the reduction of coliform bacteria, daily data, plant no. 35*

RAW WATER—Coliform Density[a]		FILTER EFFLUENT[b]			Effectivness in reduction of coliform bacteria, percent
Daily, MPN per 100 ml	Frequency days	Frequency with which 1-ml portions were coliform-positive		Coliform density, average MPN/100ml	
		Days	Percent		
≤ 230	7	4	57	[c]85	≤63.0
940	2	1	50	[c]70	92.5
2800	396	340	86	[c]196	91.5
(2100)[d]				[d]256	[d]87.8
9400	5	5	100	[c]≥240	97.4
24000	317	283	89	[c]214	99.1
(22000)[d]				[d]230	[d]99.0
≥240000	4	4	100	[c]≥240	≈99.9
Total or ≈13,000 Average (6000)[1]	731	637	87	[c]≥205 [d]249	≈98.4 [d]95.

[a] Raw water samples examined daily by 0.11-ml plantings, presumptive test.
[b] Filter effluent samples examined daily, using one 1-ml planting, presumptive (LTB) test.
[c] Estimated MPN per 100 ml = 230 $\log_{10}\left(\frac{\text{Portions planted}}{\text{Portions negative}}\right)$
[d] Estimated MPN obtained by assuming the results from each 10 consecutive daily samples for raw water loading under consideration to be those from a single sample and applying Thomas's (12) log-probability procedure.

mg/l), either with or without the addition of ammonia, followed by pumping, coagulation, and sedimentation in a plain basin (7 hours), and filtration. Postchlorination and pH adjustment completed the treatment.

Table 34 summarizes the daily bacteriological data for periods during which predisinfection was omitted with those during which it was used.

Plant 43 normally treated water by the addition of alum (30 mg/l) and chlorine (0.3 mg/l), followed by quick mixing and

TABLE 33.—*Effectiveness of lime-soda softening, coagulation, sedimentation, and filtration in the reduction of coliform bacteria, daily data, plant no. 53*

RAW WATER—Coliform density[a]		FILTER EFFLUENT[b]			Effectiveness in reduction of coliform bacteria, percent
Daily MPN per 100 ml	Frequency days	Frequency of coliform-positive samples		Coliform density, average MPN per 100 ml	
		Days	Percent		
≤ 23	34	5	14.7	2.5	≤89.1
270	348	44	12.6	2.1	99.2
1600	93	23	24.7	4.0	99.7
≥ 1600	206	33	16.0	2.2	≥99.9
5500	20	5	25.0	14.4	99.7
≥ 5500	20	6	30.0	4.7	≥99.9
36000	2	2	100.0	22.0	99.9
≥ 36000	6	2	33.3	1.9	≥99.9
≥190000	1	1	100.0	≥240.0	≈99.9
Total or average ≈1740	730	121	16.6	≥2.9	≈99.8

[a] Raw water samples examined by single tube plantings of two or more dilutions of 1.0, 0.1, 0.02, 0.01, and 0.001 ml, presumptive test. MPN calculated by Thomas's approximate method.
[b] Filter effluent samples examined by 51.0-ml plantings, completed test.

TABLE 34.—*Comparison of coliform densities in raw and filtered waters for periods during which predisinfection was used and not used, daily data, plant no. 29*

RAW WATER—Coliform density[a], daily MPN per 100 ml	FILTER EFFLUENT—Prechlorine or prechloramine disinfection: Used		Not used	
	Frequency days	Coliform density[b], average per 100 ml	Frequency days	Coliform density[b], average MPN per 100 ml
230	2	0.0	0	....
1500	110	3.7	10	84.0
10000	168	2.5	49	91.0
22000	7	3.4	18	105.0
≤35000	84	9.7	54	128.0
≤76000	44	14.7	49	96.0
≥240000	6	0.0	12	92.0

[a] Raw water samples examined using single plantings of 0.1, 0.01, and 0.004 and sometimes 0.002 and 0.001 ml, presumptive test. MPN's calculated using Thomas's approximate method.

[b] Filter effluent samples examined using one 10- and one 1-ml portions, confirmed test. For purposes of averaging the MPN has been considerd 0 if both portions were negative, and 240 if both portions were positive.

primary settling (4 hours). The water was then treated with lime (97 mg/l) and sometimes soda-ash, followed by flocculation and postchlorination.

Predisinfection was discontinued during November 28 through December 1, 1953. Bacteriological data for this period are shown in table 35. Coliform bacteria were detected in the filter effluent during 5 consecutive days starting November 29.

Plant 48 normally treated water by prechlorination (4.9 mg/l), presedimentation (34 hours), the addition of alum (12 mg/l) and sodium aluminate (0 to 4 mg/l), followed by quick mixing, floc-

TABLE 35.—*Effect of the discontinuance of prechlorination on the occurrence of coliform bacteria in the filter effluent, daily data, Plant No. 48*

Date	Prechlorine application, mg/l	Coliform density, MPN per 100 ml: Raw Water[a]	Filter effluent[b]
1953			
Nov. 17	0.3	230	<2.2
18	.3	2400	5.1
19	.3	2400	<2.2
20	.3	230	<2.2
21	.3	2400	<2.2
22	.3	2400	<2.2
23	.3	2400	<2.2
24	.3	2400	<2.2
25	.3	2400	<2.2
26	.2	230	<2.2
27	.3	2400	<2.2
28	.0	230	<2.2
29	.0	2400	5.1
30	.0	2400	5.1
Dec. 1	.0	2400	9.2
2	.3	2400	16.0
3	.2	2400	2.2
4	.2	2400	<2.2
5	.2	2400	<2.2
6	.2	2400	<2.2
7	.2	2400	<2.2
8	.2	2400	<2.2
9	.2	2400	<2.2
10	.2	2400	<2.2
11	.2	2400	<2.2

[a] Raw water samples examined using 1.11-ml plantings, 24 hour presumptive test.

[b] Filtered water samples examined using five 10-ml portions, confirmed test.

culation (½ hour) and primary settling (2½ hours). Lime (28 mg/l) and soda-ash (28 mg/l) were added and the water again flocculated (½ hour) and settled (2½ hours). After recarbonation it was filtered and postchlorinated (0.4 mg/l).

Table 36 shows the effect of discontinuing prechlorination. The residual chlorine concentrations in both settled and filtered waters

TABLE 36.—*Effect of discontinuance of prechlorination on the occurrence of coliform bacteria in the filter effluent, daily data, Plant No. 48*

Date	RAW WATER Coliform density[a], MPN/100 ml	INFLUENT TO FILTER		FILTER EFFLUENT	
		Total chlorine residual, mg/l	Coliform density[b], MPN/100 ml	Total chlorine residual mg/l	Coliform density[b], MPN/100 ml
1953 March					
1	4300	0.2	< 2.2	0.2	<2.2
2	4300	.2	< 2.2	.1	<2.2
3	4300	.6	< 2.2	.4	<2.2
4	9300	.8	< 2.2	.6	<2.2
5	4300	.2	< 2.2	.2	<2.2
6	4300	.4	< 2.2	.4	<2.2
7	930	.4	< 2.2	.4	<2.2
8	930	.2	< 2.2	.2	<2.2
9	4300	.0	16.0	.0	<2.2
10	930	.0	≥24.0	.0	5.1
11	1500	.0	≥24.0	.0	5.1
12	230	.2	≥24.0	.1	5.1
13	4300	.2	< 2.2	.2	<2.2
14	930	.4	< 2.2	.2	<2.2
15	2400	.5	< 2.2	.3	<2.2
16	24000	.4	< 2.2	.3	<2.2
17	4300	.1	< 2.2	(T)	<2.2
18	9300	.1	< 2.2	.1	<2.2
19	9300	.2	< 2.2	.1	<2.2
20	4300	.2	< 2.2	.2	<2.2

[a] Raw water samples examined by 3.333-ml plantings, confirmed test.
[b] Settled and filtered water samples examined by plantings five 10-ml portions, confirmed test.

were 0.0 mg/l for 3 days starting March 9, 1953. Coliform bacteria were found in the filter influent on 4 consecutive days starting March 9, and in the filter effluent on 3 consecutive days starting March 10.

Discussion

The results of bacteriological examinations of raw and filtered, but unchlorinated, water samples for a 2-year period at each of three plants have been summarized. At one plant the daily data for periods during which predisinfection was used are compared with those during which no predisinfection was utilized. The effect of discontinuing prechlorination for a few days is shown for two plants.

The available data include numerous indeterminates. Thus its analysis has required certain assumptions. The procedure used has been noted so that the validity of such assumptions can be evaluated by the reader.

The average coliform bacterial reductions effected by the coagulation, sedimentation, and filtration processes range from 98.4[3] to 99.8 percent for the 3 plants studied. The percentage coliform removals obtained for the least loading was ⋛77.4, ⋛63.0, and ⋛89.1 for Plants 26, 35, and 53, respectively. That for maximum coliform loadings equaled or exceeded 99.0 percent for each of these three plants. The superior performance at Plant 53 under the lower loading is attributed to the disinfecting property of the lime-soda treatment used in softening the water.

The average coliform densities in the filtered, but unchlorinated waters, ranged from ⋚2.9 to 200 per 100 ml. For all raw water loadings at all three plants it exceeded the assumed bacteriological objective for water plant effluent.

The limited data available from these three plants indicate that the bacterial efficiency of the combined processes of coagulation, sedimentation, and filtration varies from less than 80 percent for low raw water bacterial loadings to more than 99 percent under high loadings. This led to checking Streeter's studies (2) (3) to determine whether they provided evidence of such variation in bacterial efficiency. The results are shown in figure 2.

[3] The average efficiency on analyzing the data for Plant 35 by Thomas's log-probability procedure was 95.8 percent.

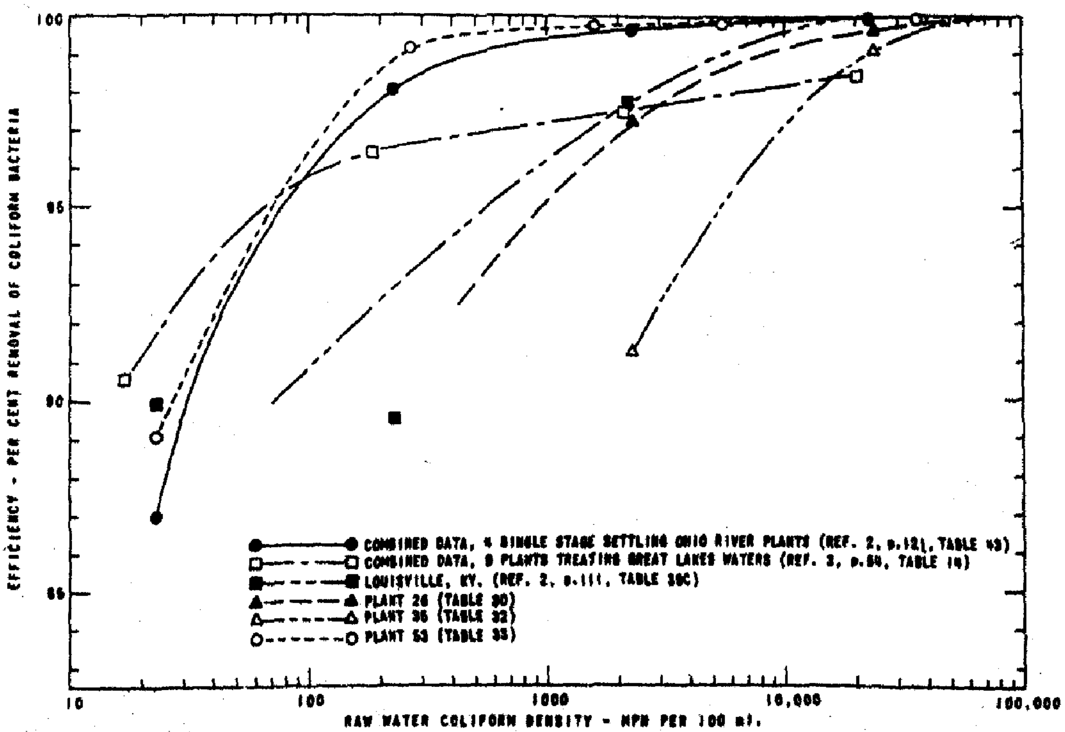

Figure 2. Effectiveness of Coagulation Sedimentation and Filtration in Removal of Coliform Bacteria

It is noted that the data from Streeter's reports has been plotted in terms of MPN. The transfer from the "Indicated Number" to MPN was made as follows. A curve showing the relation of "Indicated Number" to MPN for the results from five 10-ml portions was used for all coliform densities not exceeding 23 per 100 ml. For all other data, most of which were the result of planting one portion each of three or more decimal volumes, the MPN was assumed equal to 2.3 times the "Indicated Number." Streeter's combined data for all 9 Ohio River Plants (2) and those for six other plants (2) are not shown. The former follows the curve for the four Ohio River Plants for the higher bacterial loadings, but terminates at 92.2 percent removal when the bacterial loading is 23 per 100 ml. The raw water bacterial loading for the six other plants ranges from 540 per 100 ml upward, and these data, if plotted, would form a curve practically coinciding with that for plant 53 for loadings above 500 per 100 ml.

The curves showing the percentage coliform bacterial reductions for various raw water loadings at Plant 26, 35, and 53 differ greatly. This is believed due to the differences in the plants and their operation. The higher removal of coliform bacteria at Plant 53 is undoubtedly due to the bactericidal effect of the excess lime-soda treatment provided. Although Plants 26 and 35 treated essentially the same water, the average turbidities of the coagulated and settld waters were 6.3 and 11.6, respectively. Moreover, Plant 26 has all conventional rapid sand filters while those at Plant 35 represent the historical development of rapid sand filtration. Finally, it is noted that the coliform examination of filter effluent at Plant 35 was by presumptive test only, while those at Plants 26 and 53 were by confirmed test.

Conclusions

The limited data available show that treatment by coagulation, sedimentation, and rapid sand filtration is inadequate for the production of water conforming to accepted bacteriological requirements. The over-all effectiveness of these processes as measured by the removal of coliform bacteria varies with the bacterial loading. It may range from less than 80 percent for low raw water loadings to more than 99 percent under high loadings.

PRESEDIMENTATION

Although several of the plants pretreated water by plain sedimentation, the data from only 3 plants (Nos. 6, 25, and 32) were both adequate and satisfactory for study.

Presentation and Discussion of Data

At Plant 6 river water was presettled in a 25-mg reservoir. Using the volume of water treated, the average theoretical detention time was 7 days, and for the months of maximum and minimum pumpages it averaged 5 and 8.3 days, respectively.

Except for a 28-day period during July and August, 1954, daily samples were taken and examined for coliform bacteria. These examinations consisted of the presumptive tests of single portions in decimal series from 1 to 0.001 ml for raw water, and from 10 to 0.01 ml for settled water.

Various methods have been used to study the efficiency of presettling in coliform removal. Table 37 shows the monthly, also

TABLE 37.—*Effectiveness of presedimentation as determined by the reduction in coliform bacteria, monthly data, Plant No. 6*

Year and month	Coliform density, average MPN per 100 ml		Effectiveness in reduction of coliform bacteria, percent
	Raw water	Settled water	
1954			
January	≶ 49800	≶7400	±85.1
February	≶ 65600	≶2700	±95.9
March	≶ 24000	≶4700	±80.4
April	≶ 49200	≶3100	±93.7
May	≶ 61600	≶1800	±97.1
June	≶103000	≶4800	±95.3
July	≶ 86000	....	....
August	≶114000	≶9900	±91.3
September	≶ 83200	≶5400	±93.5
October	≶100000	≶2500	±97.5
November	≶ 50000	≶3100	±93.8
December	≶ 46700	≶1400	±97.0
Average	≶ 69500	≶4300	±93.8
1955			
January	≶ 38400	≶2600	±93.2
February	≶ 72600	≶3300	±95.5
March	≶ 30300	800	±97.4
April	≶ 63800	≶5600	±91.2
May	≶ 56000	≶2300	±95.9
June	≶ 60000	≶4500	±92.5
July	≶ 87700	≶3500	±96.0
August	≶ 88700	≶4100	±95.3
September	≶ 80100	≶5800	±92.8
October	≶ 91000	≶6000	±93.4
November	≶ 48500	≶2800	±94.2
December	≶ 59400	≶6200	±89.6
Average	≶ 64800	≶3700	±94.3

the yearly, efficiencies based on the average coliform densities for the period studied. Monthly efficiencies range from 80.4 to 97.5 percent. The annual averages are 93.8 and 94.3 percent.

A second procedure, which was used by Streeter, groups all data by days having a common coliform density in the raw water. Each group is then subdivided according to the coliform density in the settled water. Table 38 summarizes the results. The efficiency in removal varies with loading, being 98± percent with high loading and negative with low loading. A deficiency in this

TABLE 38.—*Effectiveness of presedimentation in the reduction of coliform bacteria, daily data, Plant No. 6, 1954*

RAW WATER—Coliform density		SETTLED WATER—Coliform density		Effectiveness in reduction of coliform bacteria, percent	Percentage of time
Daily MPN per 100 ml	Frequency, days	Daily MPN per 100 ml	Frequency, days		
240,000	72	≧24,000	10	±90	13.9
		2,400	43	≧99	59.7
		240	19	≧99	26.4
	Avg. or total	≧ 4,830	72	±98	100.0
24,000	222	≧24,000	30	≦ 0	13.5
		2,400	122	90	55.0
		240	70	99	31.5
	Avg. or total	≧ 4,670	222	≦80	100.0
2,400	43	≧24,000	3	neg.	7.0
		2,400	24	0	55.8
		240	16	90	37.2
	Avg. or total	≧ 3,040	43	neg.	100.0

procedure is that time for the water to flow through the reservoir has been neglected. However, a check (table 39) made using the estimated 2-day retention in the reservoir gives almost identical results.

Plant 25 presettled river water in reservoirs providing 22 mg storage. During the summer and fall months copper sulfate treatment was used for algae control. Copper sulfate was usually applied in amounts of 5 to 7 mg/l on alternate days. The theoretical detention time ranged from 5 to 10 days and averaged 7 days.

Bacteriological examinations of raw and presettled water were routinely made 6 days each week. Data for raw water are based on three plantings each of 0.1, 0.01, and 0.001 ml, confirmed test; and for presettled water on five plantings each of 0.1 and 0.01 ml, confirmed test.

TABLE 39.—*Effectiveness of presedimentation in the reduction of coliform bacteria, assuming 48-hour retention, daily data, Plant No. 6, 1954*

RAW WATER—Coliform density		SETTLED WATER—Coliform density		Effectiveness in reduction of coliform bacteria, percent	Percentage of time
Daily MPN per 100 ml	Frequency, days	Daily MPN per 100 ml	Frequency, days		
240,000	73	≧24,000	11	±90	15.1
		2,400	36	≧99	49.3
		240	26	≧99	35.6
	Avg. or total	≧ 4,890	73	±98	100.0
24,000	221	≧24,000	28	≦ 0	12.6
		2,400	129	90	58.4
		240	64	99	29.0
	Avg. or total	≧ 5,430	221	≦77	100.0
2,400	43	≧24,000	3	neg.	7.0
		2,400	23	0	53.5
		240	17	90	39.5
	Avg. or total	≧ 3,060	43	neg.	100.0

Table 40 shows the average monthly coliform data and efficiency of coliform removal. The annual percent removals were 90.5 and 90.4 percent. Average removal for 14 months during which copper sulfate was not used was 74.5 percent while that for the 10 months during which the algacide was used for at least part of the month was 94.8 percent.

TABLE 40.—*Effectiveness of presedimentation or presedimentation plus copper sulfate treatment, in the reduction of coliform bacteria, monthly data, Plant No. 25*

Year and Month	Coliform density, average MPN per 100 ml		Effectiveness in reduction of coliform bacteria, percent
	Raw water	Presettled water	
1953			
January	17700	3270	81.5
February	9300	2850	69.3
March	9800	2280	76.7
April	4600	1680	63.4
May	13000	2520	80.6
June	9900	1450	85.3
July	18300	460	[a]97.5
August	23700	390	[a]98.4
September	50000	790	[a]98.4
October	71000	780	[a]98.9
November	94900	11200	[a]88.2
December	14900	4670	68.6
Average	28100	±2680	± 90.5
1954			
January	12100	1620	86.6
February	4300	1770	58.8
March	9700	1770	81.8
April	9200	2110	77.1
May	22900	3000	86.9
June	10800	1680	[a]84.4
July	38400	390	[a]98.8
August	24700	330	[a]98.7
September	70400	810	[a]98.8
October	40300	5600	[a]86.1
November	6600	2480	59.4
December	8000	2830	64.6
Average	21400	± 2060	± 90.4

[a] Copper sulfate added, usually 5 to 7 mg/l on alternative days from July 18-Nov. 11, 1953, and from June 14-Oct. 11, 1954.

At Plant 32 river water is presettled in a 21-mg tank. The theoretical detention time ranged from 3 to 7 hours, and averaged 4½ hours.

Coliform examinations were made of raw and presettled water 5 to 6 days each week. Data from these examinations are given in table 41. In each case these examinations consisted of five plantings in each of two decimal volumes (0.1 and 0.01 or 0.01 and 0.001 ml), presumptive test.

Indicated coliform removals ranged from-7.8 to 48.2 percent. The annual averages were 17.0 and 26.8 percent for 1951 and 1952.

TABLE 41.—*Effectiveness of presedimentation in the reduction of coliform bacteria, monthly data, Plant No. 32*

Year and month	Coliform density, average MPN per 100 ml		Effectiveness in reduction of coliform bacteria, percent
	Raw water	Presettled water	
1951			
January	≦ 9300	5800	≦37.6
February	3800	≧ 3500	≦ 7.9
March	7100	≦ 6100	≧14.1
April	7200	5700	20.8
May	≦11100	≦38000	±33.3
June	≦37900	≦10500	− 0.3
July	≦16500	≦27300	±36.4
August	≦29400	≦22800	± 7.1
September	32700	≦24900	≧30.2
October	≦23100	≦14800	− 7.8
November	≦17800	≦ 7400	±16.9
December	≦ 8800		±15.9
Average	≦17100	±14200	±17.0
1952			
January	5200	3800	26.9
February	6900	6000	13.0
March	≦10000	≦9600	± 4.0
April	≦ 8500	4700	≦44.7
May	≦11300	....	....
June	≦16700	≦12000	±28.1
July	≦31000	≦16600	±46.5
August	≦11200	≦11900	− 6.2
September	10400	10200	1.9
October	≦ 9800	≦ 9200	± 6.1
November	≦ 9200	≦ 8200	±10.9
December	≦21800	≦11300	±48.2
Average	≦12700	≦ 9300	±26.8

Conclusions

The efficiency of presedimentation varies with the raw water coliform density as well as the holding time. Coliform bacterial removals of 80 percent or more are indicated for heavily loaded water held for several days. However, during periods of low bacterial loadings presedimentation may be ineffective in removing coliform bacteria.

Short-time detention of a few hours cannot be justified on the basis of removal of coliform bacteria. Indicated removals are both low and erratic.

EXCESS LIME OR LIME-SODA ASH SOFTENING, COAGULATION, AND SEDIMENTATION

Plants Studied

Data from 3 plants (Nos. 19, 32, and 36) were adequate for study of the reduction in coliform bacteria resulting from excess lime or lime-soda softening, coagulation, and sedimentation.

Plant 19 treated water by adding lime (116 mg/l), alum (12 mg/l), and occasionally soda ash (16 mg/l), followed by mixing and settling in a sludge blanket type clarifier. The pH of the clarifier effluent ranged from 8.7 to 11.4 and averaged 10.7. The theoretical detention time averaged 3.3 hours and ranged from 1.6 to 6 hours. Raw water clarifier effluent samples were examined daily using 1.111-ml and 11.1-ml total plantings, respectively, by the presumptive test.

Plant 32 used short-time presettling (4.7 hours), excess lime (92 mg/l), and coagulation with alum (5.8 mg/l) and ferrous sulfate (5.2 mg/l), followed by quick mixing, flocculation, and settling for 30 to 45 hours theoretical detention time. The pH of the water after further addition of alum, chlorine, and ammonia, and secondary settling, ranged from 8.5 to 10.4 and averaged 9.6.

Plant 36 was a purification and softening plant treating an average of 40 mg of river water daily. The initial treatment consisted of the addition of lime and short-time sedimentation. Coliform bacterial examinations, presumptive test, were made of raw and finished water samples 4 or 5 days per week.

For the 2-year period examined, the lime dosage ranged from 80 to 180, and averaged 121 mg/l. Theoretical detention time varied from 1.2 to 3.8 hours. The average was about 2½ hours. The pH of the treated water ranged from 9.4 to 10.4 and the yearly averages were 9.9 and 9.8.

Discussion

The bacteriological data for Plants 19 and 32 were analyzed by plotting log-probability curves of the data on coliform examinations of the raw and settled waters. The results are summarized in table 42. At each plant the percentage reduction in coliform bacteria decreased as the raw water coliform loading increased. That Plant 32 shows the greater removal was probably due to the longer retention period.

Table 43 summarizes the monthly data for Plant 36. The monthly average removals of coliform bacteria varied from 56 to 90 percent.

TABLE 42.—*Effectiveness of excess lime softening, coagulation and sedimentation in the reduction of coliform bacteria, Plants Nos. 19 and 32*

Plant code number	Sampling point or treatment	Coliform densities per 100 ml which were exceeded for indicated percentages of time				
		75%	50%	25%	10%	1%
19	(A) Raw Water	3000	9200	28000	78000	480000
	(B) Sludge Blanket Clarifier Effluent	180	610	2100	6200	40000
	Reduction (A-B)%	94.0	93.4	92.5	92.0	91.7
32	(A) Raw Water	5300	10000	19000	46000	86000
	(B) Primary Settling Basin Effluent	12	51	200	680	5700
	Reduction (A-B)%	99.8	99.5	98.8	98.5	93.4

TABLE 43.—*Effectiveness of excess lime treatment and sedimentation in the reduction of coliform bacteria, monthly data, Plant No. 36*

Year and month	Coliform density, average MPN per 100 ml		Efficiency in reduction of coliform bacteria, percent	Lime applied, avg. gr/gal
	Raw water	Settled water		
1953				
January	3580	500	86.0	9.25
February	10000	2350	76.5	7.42
March	4140	1790	56.7	6.36
April	5400	2000	63.0	6.27
May	7180	1550	78.4	7.21
June	19600	3680	81.2	7.25
July	16900	1870	88.9	6.50
August	8770	1960	77.7	5.92
September	8430	3100	63.2	6.73
October	6100	1560	74.4	7.14
November	8550	2070	75.8	7.31
December	8910	2220	75.1	7.80
Average	8960	2050	74.7	7.10
1954				
January	2920	675	76.9	10.51
February	3720	470	87.4	8.65
March	7770	970	87.5	8.11
April	5560	1320	76.3	7.31
May	10300	1770	82.8	6.89
June	24800	3070	87.6	6.86
July	14200	2600	81.7	6.36
August	23700	5240	77.9	5.45
September	21000	5780	72.5	4.91
October	24600	4870	80.2	4.81
November	6040	2170	64.0	6.23
December	4720	1010	78.6	6.39
Average	12400	2500	79.4	6.86

Conclusions

Limited data indicate that lime or lime-soda softening process providing high pH levels has limited disinfection value. Important factors influencing the effectiveness of such treatment for destruction of coliform bacteria are the pH level and the holding time.

Lime-soda ash treatment as practiced is inadequate for disinfection. In all cases chlorination should be the final safeguard. Effective removal or inactivation of coliform bacteria can be obtained only through additional treatment by filtration and disinfection with due consideration for the contact time and residual chlorine level required at the pH involved.

APPARENT DEFICIENCIES IN FACILITIES OR OPERATIONS AT WATER TREATMENT PLANTS

At some plants the bacteriological quality of the finished water was noticeably below average. In such cases the available information has been carefully studied in an attempt to determine the causes. The analyses made herein are hypothetical; proof would require additional study at the plant levels.

Simple Chlorination

Coliform bacteria were reported in the finished water at only one of the three plants treating water by simple chlorination. The postive samples did not occur at times of the high turbidity of the water. The recorded chlorine application and total residual levels appear to have been adequate. However, this was the only plant of this type not providing a continuous record of the residual chlorine concentration. There was also evidence which indicated a lack of close technical supervision of the treatment.

Disinfection, Coagulation, and Sedimentation

Plant S–1 treated water by presettling (100 hours) followed by the addition of alum (20 mg/1), carbon (1.2 mg/1), chlorine (4.0 mg/l), and ammonia sulfate (2.8 mg/l), after which the water was settled (35 hours) in large open reservoirs. On several occasions both the presettling time and that for settling the coagulated water were much shorter due to basins being removed from service for cleaning purposes. The residual chlorine, in the form of chloramine, averaged 1.8 mg/l, but values as low as 0.6 and 0.8 were recorded for the plant effluent during 1954 and 1955, respectively.

The records on finished water samples show that during the poorest month, 12.6 percent of all 10-ml portions examined were positive for coliform bacteria; also that for 6 of the 24 months more than 5 percent of all such portions were positive for coliform bacteria. Moreover, the plant operator reported examination of samples of scum from the outlet of the final settling tank routinely showed presence of coliform bacteria.

Although the residual chloramine level may be somewhat below a desirable average, it is believed the poor results at this plant were due to lack of filtration. The presence of coliform bacteria in the scum at the effluent end of the final settling tank indicates that coliform bacteria survive the treatment process due to being embedded in particulate matter through which chlorine may not penetrate.

Conventional Rapid Sand Filtration and Disinfection

Reference to table 13 shows that there were only four of the conventional rapid sand filtration and disinfection plants having more than 2 percent of all 10-ml portions of finished water examined during any month positive for coliform bacteria. All four of these plants are considered to have deficiencies in facilities or operation.

Two of them, Nos. 44 and 53, are excess lime or lime-soda softening plants providing marginal chlorination giving total chlorine residuals averaging only 0.1 mg/l in the finished water. Daily residual chlorine levels less than 0.05 mg/l were occasionally recorded at each of these plants. The difficulty of maintaining adequate residual chlorine when operating at a level providing such a low residual, together with the high pH resulting from the softening processes, appear to be the cause for the relatively poor records of these two plants.

Plant 8 is a purification plant producing between 5 and 10 mgd. Treatment consisted of prechlorination, coagulation with alum and lime, settling, filtration, aeration in open spray aerators, and storage followed by addition of chlorine to the suction line of the high pressure pumps. The average total residual chlorine in the treated water for the 2-year period was 0.7 mg/l.

The average annual coliform densities of the raw water exceeded 50,000 per 100 ml for each of the two years. Coliform bacteria were detected in only 3 of 502 samples of the plant effluent.

The dates on which positive samples were taken were May 3, June 1, and November 29, all during 1954. It is considered significant that immediately preceding each of these days the plant had been shut down for 24 hours or more. A possible explanation is as follows: The chlorine applied as prechlorination became depleted when the water was retained in the settling tanks an extra 24 hours and after filtration this water was exposed to air- or bird-borne contaminants in the open aerator. Finally, the postchlorination practice was such that the elapsed time between applying the chlorine and taking the sample was inadequate for disinfection.

Plant 24 is a large purification plant. Treatment normally consisted of presedimentation, the addition of chlorine, lime, and alum, followed by flocculation and settling. Additional alum was added and the water again flocculated and settled. After rechlorination the water was filtered and then flowed into an open storage reservoir from which it was pumped to the distribution system. The average annual coliform densities in the raw water were 23,000 and 28,000 per 100 ml for the years 1953 and 1954, respectively. Coliform bacteria were detected in the finished water on 6 of 730 days.

Data for these days and those immediately preceding the days on which coliform bacteria were found in the plant effluent are shown in table 44. It is noted that 14 of the positive portions occurred in three samples taken on a Saturday, Sunday, and Monday. The infrequent occurrence, the fact that the contamination was either gross or minor, and the days of the week on which the

TABLE 44.—*Coliform and chlorination data for days immediately preceding and on which coliform bacteria were detected in plant effluent, Plant No. 24*

Date		Day of week	RAW WATER Coliform density[a], MPN per 100 ml	PLANT EFFLUENT—Number of 10 ml portions		Total chlorine application, mg/l	Free chlorine residual in plant effluent mg/l
				Examined	Positive[a]		
1953							
March	29		4300	5	0		
	30		9300	5	0		
	31	Tues.	21000	5	1	5.1	0.8
1954							
Jan.	25		4600	5	0		
	26		1500	5	0		
	27	Wed.	4600	5	1	2.7	0.6
May	25		9300	5	0		
	26		9300	5	0		
	27	Thur.	4300	5	1	6.7	0.7
June	24		93000	5	0		
	25		43000	5	0		
	26	Sat.	23000	5	5	7.9	1.2
Sept.	3		4300	5	0		
	4		4300	5	0		
	5	Sun.	4300	5	4	4.3	0.9
Dec.	4		24000	5	0		
	5		15000	5	0		
	6	Mon.	15000	5	5	2.4	0.4

[a] Confirmed test.

gross contamination occurred, leads one to wonder if some of the results were not due to accidental contamination in sampling or in the laboratory. Of course, the storage of treated water in an open reservoir also provided opportunity for chance contamination.

SUMMARY DISCUSSION

This study was made to re-examine the effectiveness of various water treatment processes as measured by the reduction of coliform bacteria. It was undertaken with the knowledge that many plants were treating raw waters containing bacterial densities in excess of the recommended maximum permissible loadings established as the result of studies made by Streeter during the 1920's. That the present findings differ from those of earlier studies is due to the more intensified treatment, particularly chlorination, and to more skillful plant operation. Data from the only plant practicing marginal postchlorination, such as used by the plants studied by Streeter, substantiate his conclusions.

The data analyzed in this study were obtained from existing operating records of water plants. With one or two exceptions, the author personally visited all water plants in the United States known to have adequate data and raw water bacterial loadings frequently in excess of the Public Health Service recommendations. The data available at each of these plants were examined and, if suitable, have been utilized, even though some of them did not fully meet the standards desired. The decision to include as much data as possible was made to prevent introducing additional bias by using data from only the better operated plants of the already selected group of plants having adequate bacteriological data for survey purposes.

Throughout this study the coliform bacterial densities have been used as the sole criterion for determining the effectiveness of the treatment provided. The quality of the treated water has been based entirely on results for plant effluent samples. Data for samples collected throughout the distribution system were excluded because they would reflect contamination which occurred in the distribution system. Thus, it appeared logical to set a more stringent objective for bacterial quality of plant effluent than that required by the *Public Health Service Drinking Water Standards,* which applies to samples collected at representative locations throughout the distribution system.

Analysis of the data for conventional rapid sand filtration and disinfection plants indicates that it is practical to provide treatment such that not more than 2 percent of all 10-ml portions of plant effluent samples examined during any one month show presence of coliform bacteria. This percentage of positive portions was equaled or exceeded during only 15 of 1,281, or 1.2 percent of all plant months examined for rapid sand filtration plants. Moreover, all plant months during which two or more percent of the 10-ml portions were coliform positive occurred at only four plants and each of these plants had, in the opinion of the author, a deficiency either in facilities or operation. This analysis resulted in adopting an assumed bacteriological objective for plant effluent, which permits not more than 2 percent of all 10-ml portions of plant effluent samples examined during any one month to be positive for coliform bacteria. Failure to conform to this objective does not imply that the water delivered to the consumers is not potable. The potability of water should be evaluated by the Public Health Service Drinking Water Standards, which permit not more than 10 percent of the 10-ml portions from samples collected during any one month from representative locations throughout the distribution system to be positive for coliform bacteria.

Although a special effort was made to secure data from plants treating surface waters by simple chlorination, the total consisted of 84 plant months from only three plants. The average monthly coliform density in the raw water equaled or exceeded 100 per 100 ml during 8 plant months, and 50 per 100 ml during 33 plant months. Coliform bacteria were detected in more than 2 percent of the 10-ml portions examined during only 1 of the 84 plant months, and the raw water coliform density for that 1 month was only 27 per 100 ml. It is also noted that apparent deficiencies in operation and facilities were observed at the only plant having finished water samples showing presence of coliform bacteria.

The coliform bacteria removal effected by coagulation, sedimentation, and filtration was studied when plant data were suitable. The average removal was approximately 98 percent, which is that reported by Streeter. It should be noted, however, that the percentage removal varies greatly with the coliform density in the raw water, ranging from less than 80 percent for low loadings to more than 99 percent for high loadings. Obviously chlorination or some other form of disinfection is essential if the water produced is to meet either the assumed bacteriological objectives or the bacteriological requirements of the *Public Health Service Drinking Water Standards.*

Predisinfection, coagulation, and sedimentation provided more effective bacterial removal than the conventional rapid sand filtration process without disinfection. Results, however, are somewhat erratic. There is limited evidence indicating that bacteria embedded in particulate matter may survive chlorination.

Many water treatment plants using conventional rapid sand filtration and disinfection processes are treating raw waters heavily laden with coliform bacteria. That they can treat such waters to produce potable water conforming to the assumed bacterial-quality objection is a tribute to those individuals responsible for their design and operation.

Of the four filtration plants whose effluents exceeded 2 percent coliform positive portions in any month, two were softening plants using marginal chlorination to provide a total chlorine residual in the finished water averaging only 0.1 mg/l. Daily average residual chlorine concentrations of less than 0.05 mg/l were recorded on several occasions at each plant. The facilities at the remaining two plants provided opportunity for air- or bird-borne contamination of the filtered water.

The coliform removal resulting from presedimentation, also from excess lime or lime-soda softening has been studied where the data were available and reasonably adequate. In view of the relative small number of plants involved, the indicated removals should not be considered conclusive.

There has been considerable progress in the science and in the practice of water treatment since the period of Streeter's studies. Chlorination, together with improvements in other processes, has made it possible to treat raw waters containing coliform loadings far in excess of the permissible loadings recommended as the result of the 1920 studies. This apparent ease with which bacteria are removed or inactivated makes it essential that careful consideration be given to the use of the coliform bacterial examination as the sole criterion of biological safety of water.

Practical application of the bacteriological standard stated in *Public Health Service Drinking Water Standards, 1946,* requires that the water delivered to the consumer shall not have a coliform density in excess of 1 per 100 ml. The relation of coliform bacteria to pathogenic biological organisms has been assumed to be such that water containing that density of coliform bacteria shall be free from infectious levels of biological organisms. This raises the question whether treatment processes are equally effective in removing or inactivating other biological pathogens.

In general, epidemiological evidence supports the adequacy of the coliform bacterial examination for determination of biological safety of water produced by well-operated conventional rapid sand filtration and disinfection plants. Although there are numerous reports of water-borne outbreaks in the literature, the writer knows of only three incidents in the United States in which water apparently conforming with accepted bacteriological standards has been incriminated as the agent of transmission. These are the series of gastroenteritis outbreaks in 1930–31 which occurred in 6 cities securing water from the Kanawha and Ohio Rivers (14), the 1935 outbreak of gastroenteritis and typhoid fever in Minneapolis (15), and an outbreak of gastroenteritis in Milwaukee during 1938 (16). In two of these incidents, although the water conformed to the bacteriological requirements of accepted standards, coliform bacteria were detected in some of the potable water samples, and in the remaining case it was not determined whether the causitive agent was chemical or biological.

A review of the available information indicates that enteric viruses, such as polio, Coxsackie, ECHO, and infectious hepatitis, might be transmitted through water to produce disease in susceptible individuals. The presence of polio, Coxsackie, and ECHO viruses in sewage has been demonstrated (17) (18) and there is epidemiological evidence that virus causing infectious hepatitis survived water treatment processes (19).

If it is assumed that the removal of such viruses by coagulation, sedimentation, and filtration is of the same general magnitude as that for coliform bacteria, the effectiveness of chlorine disinfection becomes of vital importance. Laboratory investigations (20), (21), (22), have demonstrated that certain enteric viruses are more resistant to chlorine disinfection than coliform bacteria. It is also noted that *Endamoeba histolytica* survive chlorine disinfection levels which provide a complete kill or inactivation of coliform bacteria (23).

Chlorination, together with improvements in other processes, has made it possible to treat raw waters containing coliform bacterial loadings far in excess of the permissible loading recommended by the Public Health Service. The capacity of improved water treatment processes to remove bacteria suggests that waters containing coliform bacterial densities considerably in excess of present recommended loadings are acceptable for treatment. The utilization, however, of raw waters heavily contaminated with sewage may create other problems.

Although bacteria are readily removed or inactivated by water treatment processes, our knowledge of the fate of viruses and other pathogenic organisms is very limited. The problems of taste and odor, which are of major concern to water plant operators, should also be considered. Last, but not least, the psychological reaction of the public against obtaining their drinking water from "dirty water" are involved. Thus, it should be recognized that the production of a safe and desirable drinking water is most easily and economically accomplished when the plant processes a good grade raw material.

Some factors to be considered in evaluating a plant's capacity to treat water containing high densities of coliform organisms are the qualifications of the operators, the availability of adequate chlorinators, the locations at which chlorine is applied, the residual chlorine levels maintained, and the frequency of their determination. Special precautions, such as a residual chlorine recorder with alarm system, are desirable when treatment consists of simple chlorination, or where the chlorine demand of the water varies greatly over short intervals of time.

II. Special Cooperative MF-MPN Study

SUPPLEMENTARY STUDY

During 1956–57, fourteen water treatment plants throughout the United States participated with the Robert A. Taft Sanitary Engineer Center in a special study, one objective of which was to secure additional data of uniform and outstanding quality for evaluating the efficiency of water treatment plants in removal or inactivation of coliform bacteria. Ten of those water plants, data from which have been used in this paper are:

Atlanta, Ga.
Hackensack Water Co.
  New Milford, N. J.
Kansas City, Kans.
Fridley Plant,
  Minneapolis, Minn.
Quincy, Ill.
Dallas, Tex.
Kaiser Aluminum & Chemical
  Corp.[4] Chalmette, La.
Laredo, Tex.
Omaha, Nebr.
Wyandotte, Mich.

Data from the other 4 plants have not been included, as they either covered only a limited period of operation, or the plant sampling location had been selected to secure water having positive but low level coliform density.

Particular efforts were made to secure bacteriological data of outstanding quality. Consideration was given to the quality of the laboratory work in the plant selection, and all participating plants agreed to follow general procedures as outlined by the Sanitary Engineering Center. Morover, a bacteriologist from the Center spent 2 to 4 days at each plant to assist laboratory personnel in standardizing the MF procedures, and made a return visit to the plant if difficulties were encountered. EHC powder indicator for all MF examinations was supplied by the Center. Finally, only the last 12 of the 13 months of data from each plant have been utilized.

In general, raw water and plant effluent samples were examined 5 days each week, except during the last 2 weeks of December, when collection of data was omitted due to anticipated delay in receipt of the delayed MF samples mailed to the Center.

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[4] Bacteriological examination of water samples from Kaiser Corp. Water Plant were made by Division of Laboratories, Louisiana State Department of Health.

Portions of raw and finished water samples were examined by each of three procedures–MPN dilution, immediate MF, and delayed MF. All laboratory work, except that involved in the completion of the delayed MF procedure, was performed at the water plants.

Although portions of each raw water sample were examined by each of the procedures, only the results of the MPN dilution, confirmed test, are used in this report. For plant effluent, data for all three procedures are included. In these tests, the lower limits at which coliform bacteria were detectable by the MPN dilution procedure were 2.2, 1.0, and 0.69 per 100 ml at 6, 1, and 3 plants; by immediate MF procedure, 0.5, 0.25, and 0.14 per 100 ml at 6, 3, and 1 plants; and by delayed MF procedure, 0.5, 0.25, and 0.14 per 100 ml at 2, 7, and 1 plants, respectively.

Presentation of Data

Only data for those days on which results by all three bacteriological procedures were available have been used. In table 45 the data for all plants are first grouped according to raw water bacteriological density, then by the percentages of days in each group on which coliform were detected in the plant effluent by any and each procedure, and days on which one or more of the three procedures indicated that coliform densities in the treated water were equal to or greater than 1 per 100 ml.

The fact that coliform bacteria were detected in plant effluent samples on days during which raw water loadings were in excess of 50,000 per 100 ml at only 1 plant, led to further analysis. Table 46 compares the coliform data from this plant (1x) with those from Plant 5, the only other plant treating raw waters having a similar range in coliform density. In table 47 plant (1x) data for the first 6 months of the study are compared with those obtained during the last 6 months.

The coliform data for all days on which coliform bacteria were detected in plant effluent samples are given in table 48. On 54 days coliform bacteria were detected by only 1 of the 3 procedures used in examining each sample. Such detection occurred nine times by MPN dilution, 13 times by immediate MF, and 32 times by delayed MF procedure. Portions of seven samples were positive for coliform bacteria by two procedures, once by MPN dilution and immediate MF, twice by MPN dilution and delayed MF, and four times by both MF procedures. All three procedures detected coliform bacteria in only four samples.

Altogether, coliform bacteria were detected in one or more portions of 65 plant effluent samples. Positive results were obtained 16 times by the MPN dilution procedure, 22 times by the

TABLE 45.—*Effectiveness of conventional rapid sand filtration and disinfection water treatment plants in the reduction of coliform bacteria, daily data, special MF-MPN study*

RAW WATER—Coliform density, Daily MPN/100 ml	RAW WATER—Coliform density, Frequency, days	PLANT EFFLUENT—Percentage of days on which— Coliform bacteria were detected by— Any process	MPN Dil. Proc.[a]	Immed. MF Proc.[b]	Delayed MF Proc.[c]	Coliform Density ≥1 per 100 ml Any Proc.	MPN Dil. Proc.[a]	Immed. MF Proc.[b]	Delayed MF Proc.[c]
0- 2400	1058	2.6	0.4	1.0	1.2	1.0	0.4	0.3	0.4
2500- 4900	323	1.9	1.2	.0	.6	1.2	1.2	.0	.0
5000- 9900	199	2.5	1.0	.5	2.0	1.0	1.0	.5	.5
10000- 24000	318	3.8	1.3	.6	3.1	1.3	.3	.3	.6
25000- 49000	199	2.5	.5	1.0	2.5	1.0	.5	1.0	1.0
50000- 99000	85	[d]4.7	.0	[d]2.4	[d]3.5	.0	.0	.0	.0
100000-240000	77	[d]9.1	[d]1.3	[d]5.2	[d]6.5	[d]5.2	[d]1.3	[d]3.9	[d]3.9
250000-490000	14	.0	.0	.0	.0	.0	.0	.0	.0
500000-990000	12	.0	.0	.0	.0	.0	.0	.0	.0
≥1,000,000	4	.0	.0	.0	.0	.0	.0	.0	.0

[a] Limits of detection: 2.2/100 ml for 6 plants; 1/100 ml for 1 plant and 0.69/100 ml for 3 plants.

[b] Limits of detection: 0.5/100 ml for 6 plants; 0.25/100 ml for 3 plants and 0.14/100 ml for 1 plant.

[c] Limits of detection: 0.5/100 ml for 2 plants; 0.25/100 ml for 7 plants and 0.14/100 ml for 1 plant.

[d] All positive data from plant 1x.

TABLE 46.—*Comparison of coliform data for raw and finished waters for periods of special MF-MPN study at Plants, 1x and 5, daily data*

Raw water coliform density, MPN per 100 ml	PLANT NO. 1x — Frequency of raw water coliform density, days	PLANT NO. 1x — Percentage of days on which coliform bacteria were detected in plant effluent at— Any level	PLANT NO. 1x — ≥1/100 ml	PLANT NO. 5 — Frequency of raw water coliform density, days	PLANT NO. 5 — Percentage of days on which coliform bacteria were detected in plant effluent at— Any level	PLANT NO. 5 — ≥1/100 ml
0- 2400....	1	0.	0.	1	0	0
2500- 4900....	3	0.	0.	10	0	0
5000- 9900....	6	0.	0.	14	7.2	0
10000- 24000....	51	0.	0.	09	1.4	0
25000- 49000....	67	3.0	3.0	72	0	0
50000- 99000....	28	14.3	0.	21	0	0
100000-240000....	40	15.0	10.0	28	0	0
250000-490000....	13	0.	0.	1	0	0
500000-990000....	11	0.	0.	1	0	0
≥1,000,000.......	1	0.	0.	3	0	0
Total or Average..	224	5.4	2.7	220	0.9	0.0

TABLE 47.—*Comparison of coliform data for raw and finished waters for first and second six-month periods of special MF-MPN study, daily data, Plant No. 1x*

Raw water coliform density, MPN per 100 ml	First 6 months			Second 6 months		
	Frequency of raw water coliform density, days	Percentage of days on which coliform bacteria were detected in plant effluent at—		Frequency of raw water coliform density, days	Percentage of days on which coliform bacteria were detected in plant effluent at	
		Any level	≥1/100 ml		Any level	≥1/100 ml
0- 2400....	0	....	....	1	0.	0
2500- 4900....	0	....	....	3	0	0
5000- 9900....	2	0	0	4	0	0
10000- 24000....	16	0	0	38	0	0
25000- 49000....	29	6.9	6.9	38	0	0
50000- 99000....	17	17.7	0	11	9.1	0
100000-240000....	26	23.0	15.4	14	0	0
250000-490000....	7	0	0	6	0	0
500000-990000....	10	0	0	1	0	0
≥1,000,000.......	1	0	0	0	....	....
Total or Average..	108	10.2	5.6	116	0.9	0.0

immediate MF procedure, and 42 times by the delayed MF procedure. It should be noted that the apparent differences in frequencies with which the various procedures detected presence of coliforms disappear on considering only that data showing densities ≥1/100 ml. At or above this density the frequencies of detection were 13, 10, and 12 by MPN dilution, immediate MF, and delayed MF procedures, respectively.

Table 48.—*Comparison of Coliform densities of raw and finished waters for all plant days on which coliform bacteria were detected in plant effluents, special MF-MPN study*

Plant code number	RAW WATER—Coliform density, MPN per 100 ml	PLANT EFFLUENT—Coliform density per 100 ml as determined by—		
		MPN dilution procedure	MF immediate procedure	MF delayed procedure
51	11	2.1	< 0.25	<0.25
38	50	< .69	.5	< .5
50	110	< 2.2	< .5	.25
51	130	< 2.1	.25	< .25
33	170	< 2.2	< .5	.25
50	220	< 2.2	< .5	1.0
50	230	< 2.2	< .5	11.8
51	230	< 2.1	< .25	.25
38	230	< .69	.5	< .5
50	330	< 2.2	< .5	.5
51	490	< 2.1	.25	< .25
50	690	< 2.2	< .5	12.8
50	700	< 2.2	< .5	.25
50	790	< 2.2	< .5	2.25
24	790	2.2	< .5	< .25
50	1300	< 2.2	.5	< .25
33	1300	< 2.2	1.0	< .25
50	1700	< 2.2	< .5	.25
19	1700	< 1.0	1.2	< .25
24	1700	2.2	.5	< .25
24	1700	2.2	< .5	< .25
38	2200	< 2.2	< .5	.25
24	2300	< 2.2	2.0	< .25
38	2300	< .69	< .33	.33
50	2400	< 2.2	< .5	.5
19	2400	< 10	.25	< .25
38	2400	< .69	.33	< .33
19	2600	≤ 1.0	< .5	< .5
19	3300	< 1.0	< .25	.25
50	3500	5.1	< .5	< .25
24	3500	2.2	< 0.5	<0.25
20	4500	< 2.2	< .25	.25
24	4900	≤ 23.0	< .5	< .25
5	6800	< .65	< .14	.14
24	7900	< 2.2	< .5	.25
24	7900	< 2.2	< .5	.25
38	7900	1.1	< .33	< .33
38	7900	1.1	1.0	6.3
24	13000	< 2.2	< .5	.25
2x	13000	< .65	< .5	.25
24	13000	< .22	3.0	< .25
38	13000	< .69	< .33	.67
38	13000	< .69	< .33	1.67
38	13000	< .69	< .33	.33
38	13000	< .69	< .33	.33
5	22000	.68	.28	.28
38	22000	< .69	.33	1.67
24	24000	2.2	< .5	< .25
38	24000	.69	< .33	.33
38	24000	.69	< .33	.33
19	28000	< 1.0	< .25	.25
1x	33000	< 2.2	11.0	7.0
1x	33000	16.0	3.5	3.0
50	35000	< 2.2	< .5	.25
38	35000	< .69	< .33	.33
1x	79000	< 2.2	.5	.5
1x	79000	< 2.2	.5	< .5
1x	79000	< 2.2	< .5	.5
1x	79000	< 2.2	< .5	.5
1x	130000	< 2.2	4.5	1.5
1x	130000	< 2.2	< .5	.5
1x	170000	< 2.2	.5	1.5
1x	240000	< 2.2	1.5	< .5
1x	240000	2.2	6.0	5.0
1x	240000	< 2.2	< .5	.5

Discussion

The maximum daily coliform densities in the raw waters exceeded 50,000 per 100 ml at 9 plants, 100,000 per 100 ml at five plants, and 250,000 per 100 ml at two plants. In spite of such heavy loadings coliform bacteria were detected in only 2.8 percent of all plant effluent samples, and at a level $\geqq$ 1 per 100 ml in only 1.2 percent of these samples. Excluding the data from Plant (1x) only 0.73 percent of all plant effluent samples were determined by any one of three procedures to contain one or more coliform bacteria per 100 ml.

Examination of the MPN dilution coliform data for Plant 1x effluent samples shows that the efficiency of this plant in removing or inactivating coliform bacteria was poor compared with that of other plants. A comparison of data from this plant with those from Plant 5, the only other plant treating raw water having a similar range in coliform density, indicates either the facilities or operation of Plant (1x) were responsible for its relatively poor efficiency. The marked improvement in the bacterial quality of the water produced by Plant (1x) throughout the final 6 months period indicates that the plant facilities were adequate. This improved treatment is believed due to increased chlorination. During the first 6 months the total residual chlorine in 7 of 17 samples collected from one or more locations in a relatively restricted distribution system did not exceed 0.10 mg/l while the minimum residual chlorine in all 20 such samples collected during the second 6 months period was 0.20 mg/l.

The comparison of the results of examination of plant effluent samples by three different procedures is interesting. First, it should be remembered that all three procedures were consistent in that they gave negative results for 2,217 or 97.1 percent of all samples. Such consistency does not exist for those samples in which coliform were detected. For 19, or 29 percent of coliform-positive samples, 1 of the 3 procedures gave coliform densities 4 or more times that density at which these bacteria should have been detected but were not by at least one of the other procedures. Some of these discrepancies may have occurred through errors in technique, others by chance.

Conclusions

The special MF-MPN study provided coliform data of superior quality and procedures capable of detecting bacteria at low densities.

Nine of the 10 participating plants produced water conforming to the assumed coliform bacterial objective for plant effluent.

The records for the only plant which produced water of questionable quality during the early part of the study, but water of excellent bacterial quality throughout the last 6 months, demonstrate the importance of adequate chlorination.

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