Slow Sand Filtration and Direct In-Line Filtration of a Surface Water

by

(± 1982)

John L. Cleasby
Anson Marston Distinguished Professor of Engineering
Professor of Civil Engineering
Iowa State University
Ames, IA 50011

INTRODUCTION

Some communities served by protected upland surface water supplies presently provide no treatment except for disinfection. This is especially common for small communities. Such supplies may exceed the EPA Maximum Contaminant Level (MCL) for turbidity (1 NTU) in public water supplies during some seasons of the year. Furthermore, a number of water-borne disease outbreaks have resulted in such communities.

Such communities are faced with the need to construct and operate some form of water treatment which will consistently produce water that will protect the public health and meet the drinking water standards. For the small community, simplified treatment systems are needed which will require a minimum level of operator skill for effective operation, yet will provide a system that will ensure acceptable levels of treated water quality.

The research reported herein was directed to the above problem, and in recognition of the following developments and concerns:

1. The concern over potential Giardia transmission by public water supplies.
2. The growing use of direct filtration for high quality raw waters. Direct filtration either eliminates flocculation or reduces the flocculation detention time required, and omits sedimentation entirely.
3. The recognition that the "old" slow sand filtration concept still has potential applications on high quality raw waters with the advantage of eliminating chemical pretreatment. The slow sand filter is a lower level of water treatment technology and thus offers the potential advantages of less operational attention and less skilled personnel required for the operation. Therefore, the application to small systems with adequate land available may be attractive.

LITERATURE REVIEW

Waterborne Outbreaks of Giardiasis and Treatment Deficiencies

The need for adequate treatment of small community water supplies has been amply demonstrated by a number of recent outbreaks of waterborne Giardiasis and other waterborne diseases of bacterial or undefined origin (4,5,8,9,10).

Rome, N.Y. experienced an outbreak of Giardiasis in 1974 and 1975 with 4800 to 5300 estimated cases based on an epidemiological stud

Rome was served by a surface water source with chlorine and ammonia disinfection as the sole treatment. At the time of the outbreak, chlorine and ammonia were applied together to produce chloramine with a combined chlorine residual of 0.8 mg/l.

Camus, Washington had an outbreak of Giardiasis in 1976 which affected 600 individuals in a population of 6000 (8). Camus is served by both surface water and groundwater. The surface water was being treated by prechlorination in the transmission line to the plant with coagulant chemical addition at the plant followed immediately by filtration through multi-media pressure filters. Giardia cysts were isolated in the surface water entering the plant and Giardia positive beavers were trapped in the watershed. The treated water reportedly met coliform and turbidity standards prior to and during the outbreak.

However, a number of deficiencies were found in the condition and operation of the filters and in the chemical pretreatment at Camus. Substantial loss of filter media had occurred and gravel mounding in the filters was reported. Both of these deficiencies could reduce the effectiveness of filtration. Three periods of loss of chlorine application occurred during the outbreak, but the onset of the outbreak preceded the first chlorination failure. The raw water turbidity during the period of concern rarely exceeded the 1 NTU standard for finished water, and the finished water continuously met the turbidity and bacteriological standards set by the Safe Drinking Water Act. It was concluded from this experience that "turbidity and coliform count alone are inadequate parameters on which the judge the biological quality of filter effluent."

A similar outbreak involving a filtered water supply occcurred in Berlin, New Hampshire in which 750 cases of giardiasis occurred in 1977 (9). The raw water was derived from two river sources from which Giardia cysts were recovered. Water from one source received pressure filtration without chemical pretreatment. Water from the other source was treated by a new plant providing chemical addition (alum, polymer, and sodium hydroxide), upflow clarification and rapid sand filtration. Both plants provided post chlorination. The pressure filters of the first plant were found to be in poor condition. Serious mounding of the surface of the medium, deep cracks in the medium along the walls, mud masses and clogged areas were found. The air scour of one filter was broken so that all the air delivered during the backwash routine came out at one location causing a deep depression in the surface of the filter medium.

With such filter deficiencies, it is little wonder that the filters did not provide good filtrate. Short circuiting through the cracks and depressions would occur, and the clogged areas would be inactive, forcing excessive flow rates through the unclogged areas. This represents a classic example of why some regulatory agencies do not permit pressure filters on surface water supplies (14).

Faulty construction of a common wall between the raw and treated water of the new plant permitted an estimated 3% of filter influent water to bypass the filters. This is another classic example of why most regulatory agencies do not allow common walls to exist between unfiltered and filtered water.

In spite of these deficiencies, routine bacterial samples collected from the distribution system prior to and during the outbreak did not violate coliform standards, leading the authors to conclude that "the coliform standard is not an acceptable indicator of safety where Giardia cysts are present."

Other outbreaks of giardiasis have also occurred at Vail, Colorado in 1978 with 5000 cases (11): at Bradford, Pennsylvania in 1979 with an estimated 2900 people affected (10); and at Red Lodge, Montana in 1980 (personal communication, E.C. Lippy, Aug. 19, 1980). The outbreak at Vail was the result of inadequate filtration of surface water. The Bradford outbreak was the result of no treatment except chlorination for a surface supply, and the chlorination facilities were antiquated, had inadequate capacity, and the residual chlorine level was not properly maintained. The Red Lodge, Montana outbreak resulted from using only chlorination of a surface water with dosage levels below the cysticidal dose for Giardia cysts.

In spite of the weaknesses evidenced by the filters in the outbreaks described above, one would expect that granular deep-bed filters should do a good job in removing Giardia cysts if the filter were properly operated and maintained. The cysts are fairly large, being about 8 to 12 μm by 7 to 10 μm (11), and they exhibit a negative zeta potential of about -25 millivolts (11). Thus, they should respond favorably to normal water treatment practices designed to remove negative particles commonly encountered in water.

It is apparent from the foregoing that the practice of providing only chlorination for protected-watershed, high quality, surface waters is not adequate to ensure protection of the public health. Furthermore, routine surveillance tests for coliform organisms and turbidity with satisfactory results do not give absolute assurance that a Giardiasis outbreak cannot occur if Giardia cysts are present in the raw water.

It is apparent from the foregoing that more than one barrier to disease transmission is needed to give added reliability to the system (11). Furthermore, each barrier such as disinfection and filtration must be designed, operated and maintained so that it serves its function effectively. The operation and maintenance requirements are especially difficult to ensure in the very small community. Thus, the treatment system should be as simple, foolproof, and fail-safe as possible to ensure the highest possible degree of public health protection.

Repid Filtration Technology

If rapid filtration of surface water supplies is used as the second barrier for public health protection, it should be done in full recognition of its strengths and weaknesses. For example, it is well known that the quality of the filtered water is poorer at the beginning of the filtration cycle and may also deteriorate near the end of the cycle (1,2). Furthermore, any sudden increases or decreases in filtration rate on a dirty filter can cause breakthrough of deposited solids into the effluent (3).

The initial water quality degradation period has also been demonstrated in recent studies using Giardia cysts (11). Giardia muris was used as a model for the human pathogen, Giardia lamblia. G. muris was spiked into a low turbidity surface water, coagulated with alum alone or alum and cationic polymer, flocculated and filtered through granular media filters. Initial cyst concentrations in the filtrate were from 10 to 25 times higher than those following the initial improvement period.

In conventional water treatment practice, the turbidity passage during the initial degradation and improvement period is small, averaged over the entire filter run. Therefore, the early practice of filtering to waste at the beginning of the filter fun, to eliminate the turbidity carried through into the finished water, has been largely abandoned. It is evident that elimination of the "filter-to-waste" period may not be justifiable in the light of recent trends to use of higher filtration rates in direct filtration applications. Also, it would be unacceptable where Giardiasis is of concern because of the low ineffective dose for Giardia transmission (8) and the resistance of Giardia cysts to disinfection.

Evidence was presented in 1963 (3) showing the deleterious effect on the quality of filtered water when sudden rate increases are imposed on a dirty filter. The amount of material flushed through the filter was greater for sudden rate increases than for gradual changes. The amount of material released was greater for large increases than for small increases, but the amount was not affected by the duration of the maximum imposed rate. Different types of suspended solids encountered at different water plants exhibited different sensitivities to the rate increases. Similar observations have been reported in later papers (6, 15). These observations are important in any filtration decisions. Sudden rate increases on dirty filters should be avoided or minimized.

The recent studies by Logsdon et al. (11) also showed similar effects when the filtration rate was suddenly increased from 11 to 27 m/h. Turbidity in the effluent rose sharply and then rapidly declined. G. muris cyst concentrations followed the turbidity trends. "A four-fold increase in turbidity was accompanied by a twenty-five fold increase in cyst concentration in the filtered water." The same study demonstrated the detrimental effect of loss of coagulant feed, and of extending the filter run into the period of terminal breakthrough. In both instances, large increases in cyst concentration were observed in the effluent. Thus, filtration systems which provide no effluent rate manipulation look very attractive.

Slow Sand Filtration Technology

If slow sand filtration is added as the second barrier for added public health protection, much can be gained from early studies of slow sand filtration. The early slow sand filters used very fine sand, usually between 0.2 and 0.4 mm effective size and sometimes even smaller (7). They were operated at low rates between 3-5 million gallons per acre per day (0.05-0.08 gal/min sq ft). Such filters continue to be used successfully in England, notably on the Thames River serving London, and in the USA on some upland watersheds in New England. However, it was well recognized before 1900 in England that several days of plain sedimentation were required ahead of the filters to remove the heavier sediments, thus lengthening the filter cycles. Later, rapid filters without coagulants were used ahead of the slow sand filters for the same purpose. Even with both of these provisions typical cycle lengths on the Thames river water are only about 6 weeks.

Slow sand filters were not successful on the clay-bearing river waters typical of most of the USA. Nevertheless, some slow sand filters continue in service on high quality, protected upland watersheds where clay is not a prominent problem. Since some of the small communities needing filtration as a second barrier are located in mountainous or upland watersheds, the slow sand filter may be one viable alternative.

However, some of the same concerns discussed earlier for the rapid filter are appropriate for the slow sand filter. Water produced during the initial period of the cycle of the slow filter is of poorer quality until the dirty skin develops on the sand surface. The dirty skin, which is composed os living organisms and other debris from the water, ultimately becomes the effective filtering medium. The question remains whether the filter can provide dependable Giardia cyst removal during that initial period.

OBJECTIVES

The specific objectives of the work reported herein are:

1. Compare the performance of slow-sand filters with conventional, rapid filters during direct filtration of surface water for the removal of particulates as measured by particle counting, turbidity, coliforms, and standard plate count. The slow sand filters would be operated without chemical pretreatment while the rapid filters would receive water pretreated to destabilize the suspended solids.
2. Focus attention on those portions of a filter run where filter performance would be subject to less than normal performance:
   - During the period immediately after backwashing the filter, when the filtered water quality first degrades and then improves to the level normally observed during the majority of the filter run.
   - During the "breakthrough period" when the filtered water quality gradually deteriorates to unacceptable quality.
3. Use the results of the research to provide recommendations for design and operation of filters for small water supplies, not only to meet the turbidity standards of the Safe Drinking Water Act, but also to achieve the best possible filtrate.

EXPERIMENTAL WORK

To accomplish the above objectives, a pilot plant was constructed and erected at a local gravel pit which could provide a high quality raw water (at least during most seasons of the year). The pilot plant illustrated in Fig. 1 included the following filters:

Rapid Filter	4 inch ID, 115 inch tall housing
Slow Filter	30 inch ID, 108 inch tall housing

Media	Depth (in.)	Effective size (mm)	Uniformity Coeff.
Rapid Filter			
Anthracite	16	1.54	1.18
Sand	12	0.43	1.53
Slow Filter			
Sand	37	0.32	1.44

Raw water was pumped to a splitter box mounted above the filters. The flow to be filtered was selected by the size of orifice delivering flow to each filter. The orifices were operated under a constant head created by an overflow weir which delivered excess flow to waste.

Flow from the splitter box to the rapid filter was collected in a funnel and carried by hose to the filter. Coagulating chemical was injected into the inlet hose upstream of a static mixing device.

Both filters were operated as influent flow splitting filters in which the water level rises as the filter clogs. The effluent from each filter passed through a flow meter and a Hach 1720 continuous turbidimeter. The effluent from the turbidimeter exited above the level of the filter media to prevent dewatering the filter in the event of temporary pump failure, and to prevent negative head in the filters. The treated water flowed through a backwash storage tank used only for the backwash of the rapid filter.

The influent to the splitter box was spiked with a small amount of sewage,(usually secondary effluent, occasionally primary effluent) obtained at the local treatment plant to raise the level of coliforms and other bacteria to permit a better evaluation of bacterial removal. Total coliforms and standard plate count were determined on influent and effluent grab samples following Microbiological Methods (12) and the current edition of Standard Methods (13).

The unspiked filter influent and the two filter effluents were monitored for turbidity and particle count. Turbidity from three Hach 1720 turbidimeters was continuously recorded on a multipoint recorder. Grab samples were also measured on a Hach Ratio turbidimeter which was used as a primary standard to adjust any drift in the 1720 turbidimeters. The calibaration of the Ratio turbidimeter was checked quarterly using fresh formazin standards.

Particle counting was done on a Hiac Particle Counter with 60 μm aperture. Counts were obtained in 12 channels from 1 μm to 60 μm in size. The particle counter was calibrated every 6 months against suspensions of known particle distribution obtained fresh from the Hiac Company at the onset of the project. The counter was remarkably stable from one calibration to the next. Low particle count water was prepared by passing building distilled water through a Whatman No. 5 filter paper and a mixed bed deionizing column. This water was used for dilution of influent samples if necessary. Blanks of the dilution water were counted each time to insure consistent quality.

Head loss was indicated by a single piezometer tube for each filter which was read manually for the slow filter. The rapid filter head loss was read manually during the first six months, and later recorded on a Barton circular chart recorder (in addition to manual readings).

Other water quality parameters were measured on biweekly grab samples of the raw lake water. These parameters included alkalinity, hardness, specific conductance, suspended solids, total phosphate, orthophosphate, ammonia, nitrite, nitrate and Kjehldahl nitrogen, soluble S_iO_2, COD and Chlorophyll A, B and C. In addition, samples of the slow filter influent and effluent were monitored approximately weekly for dissolved oxygen (DO) to observe the progressive effects of biological activity in the filter on the DO. During two serious algae blooms, raw samples were enumerated for the dominant algal species present. All chemical analytical methods were in accordance with Standard Methods (13) or the EPA Methods for Chemical Analyses of Water and Wastewater (EPA 600/4-79-020, Mch, 1979).

FILTRATION RESULTS

The pilot plant was operated from Oct. 6, 1981 through Dec. 9, 1982 in order to obtain data during the full range of seasons. The winter of 1981-82 was unusually severe with extremely low temperatures and heavy snow. The snow melt runoff in the spring of 1982 and the heavy rains thereafter raised the water level higher than it had been in several years, and carried substantial plant nutrients into the quarry which resulted in a series of algal blooms. These blooms had a dramatic impact on the filtration results as will be shown later.

During the spring and summer of 1982, chloraphyll levels were much higher than in the preceding two-year period. The chlorophyll results are presented in Table 1. During the worst algal blooms, the quarry resembled a sewage lagoon in its green color. A sample collected on 7/28/82 during the period of extreme chlorophyll level was enumerated. The predominant taxa was Aphanizomenon flos-aquae, a blue green algae counted at 2913 filaments/ml (10 cells per filament). Total standing crop was 4330 cells (or filaments) per ml.

Slow Sand Filtration Results

The slow sand filter was operated at a rate of 0.12 m/h approach velocity (3.1 million gallons per acre per day). The maximum terminal head loss available to the overflow of the filter was 135 cm and filter filter runs were terminated when the overflow headloss was reached. The length of the filter runs varied substantially through the four seasons, as shown in Table 2. The best raw water occurred during the winter under the ice and this coincided with the longest runs of 123 days. The shortest runs at 9 days each occurred in the summer during periods of severe algal blooms.

Table 2. Slow Sand Filter Runs

Run No	Started	Ended	Length (days)	Initial head loss (cm)
A	10/19/81	11/22	34	10
B	12/1/81	4/3/82	123	8
C	4/7/82	4/29	22	16
D	5/5	5/18	13	17
E	5/25	6/6	12	18
F	6/10	6/19	9	18
G	6/23	7/14	21	18
H	7/21	7/30	9	18
I	8/4	8/24	20	17.5
J	9/15	10/26	39	18.8
K	11/2	12/9	37* (at 81 cm head loss)	20.5

In spite of the wide variation of run length associated with the varying raw water quality, the filtrate quality was consistently good. Typical results showing turbidity versus time for Runs A, B, F and G of the slow sand filter are presented in Figures 2 through 5. Note that the first two days of the run are shown on an expanded time scale to permit better illustration of the initial improvement period of of the filter run. The filtrate turbidity of the first two runs (A & B) was higher than all subsequent runs. The turbidity of the later runs was consistently about 0.1 NTU except during the initial improvement period. The initial improvement period was less than two days' duration, except possibly for the first two runs.

Run B is interesting because it shows the gradual improvement in raw and filtrate quality after the ice formed on the quarry, and then the sudden deterioration of raw water quality when snow melt runoff began reaching the quarry. During the transition, a ten to fifteen fold increase in raw water quality resulted in only a two-fold increase in filtrate quality.

Typical particle count data (Figures 6 through 8) looked very much like the turbidity data, showing the same trends. Only a limited number of samples were taken for analysis each week so that data points are less numerous. Because of our interest in Giardia cyst sized particles, the figures present the number of 7 to 12 μm sized particles per ml. The data for the total number of particles (1-60 μm) showed the same trends but were about an order of magnitude higher than the 7 to 12 μm particles.

Particle count data in the 7-12 μm size range for all slow sand filter runs is summarized in Table 3. This table presents the mean influent and effluent counts during two periods, the initial 2 days of the run and the remainder of the run. The number of individual samples averaged is shown in parentheses. Because Run B was long and had substantial trends in influent particle count, the data for the run have been subdivided into 4 periods during the run. Similarly, in a few other runs, the first two days have been averaged separately for the two periods.

Several things are evident in Table 3 (i). Removal in the first 2 days is worse than in the remainder of the run with the exception of Run B and C (ii). Low influent counts generally result in lower percent reductions than high influent counts. This is evident in Run B and D (iii). After Run D, the % removal was consistently high, never below 96.9% and generally above 99%. Thus the filter improved over the series of runs.

Total coliform data were less consistent than turbidity or particle count data. This was due to an inconsistent influent level obtained by spiking the influent with sewage. Typical results for the slow sand filter are shown in Figures 9 through 11 for runs B, G and J.

Mean influent and effluent levels of total coliforms are summarized for all runs in Table 4. Mean effluent levels are divided into two time periods, the first two days of the run and the remainder of the run. This Table shows trends which are similar to the particle count data of Table 3. In Table 4, the first two days are always poorer than the remainder of the run. There is a trend for better removal over the series of runs. Runs F through K are above 99% removal, (except during the first two days). Total coliform removals are similar, but generally slightly higher than 7-12 μm particle removals shown in Table 3.

The standard plate count data were very erratic during the entire study. It is assumed that some bacteria were propagating in the effluent piping flow meter and turbidimeter, and were released into the filtrate in an unpredictable pattern. In some cases, the effluent standard plate count exceeded the influent. Because of these difficulties, the data are not presented herein.

Results of Direct In-Line Filtration

Since the emphasis of this research was on small treatment systems,

Table 3. Particles per ml in influent and effluent of slow sand filter in 7-12 μm size range.

Run No.	Influent Mean (#)	Effluent First two days Mean	(#)*	% Red	Effluent Remainder Mean	(#)*	% Red.
A	2242 (10)	70	(2)	96.9	13	(12)	99.4
B	2857 (3)	33	(6)	98.8			
B (12/3-16/81)	1169 (4)				102	(5)	91.3
B (12/16-2/17/82)	265 (16)				29	(19)	89.1
B (2/17-4/3/82)	1534 (12)				15	(12)	99.0
C	3745 (7)	59	(6)	98.4	95	(6)	97.5
D	2412 (2)	104	(5)	95.7			
D	366 (2)				41	(2)	88.8
E	1425 (2)	69	(7)	95.2			
	15732 (2)				46	(1)	99.7
F	10305 (2)	48	(4)	99.5	18	(2)	99.8
G	1704 (7)	37	(5)	97.8	12	(5)	99.3
H	6713 (1)	41	(3)	99.4			
	20841 (2)				63	(2)	99.7
I	5460 (1)	412	(3)	92.4			
	736 (4)				23	(4)	96.9
J	753 (10)	34	(6)	95.5	5	(8)	99.3
K	908 (10)	47	(4)	94.8	11	(10)	98.8

* Number of individual values used to calculate the mean value.

Table 1. 1981-82 Chlorophyll A Concentrations in Hallett's Quarry Raw Water (mg/m^3)

Date 1981	Chlor A mg/m^3	Date 1982	Chlor A mg/m^3	Date 1982	Chlor A mg/m^3	Date 1982	Chlor A mg/m^3
11/9	2	3/3	0.9	7/12	28.2	11/15	0.7
11/23	1.8	3/10	0.4	7/20	4.6	11/17	0.7
12/2	2.6	3/15	1.8	7/26	132.4	11/29	1.1
12/7	3.2	3/17	1.1	7/28	130.7		
12/9	3.5	3/29	3.1	8/9	6.1		
12/14	4	4/13	6.5	8/11	4.8		
		4/26	59.5	8/18	2		
1982		4/28	57.2	8/23	3.6		
1/4	4	5/10	2.8	9/8	4.0		
1/6	3.3	5/13	14.2	9/10	2.9		
1/18	1.3	5/18	7.8	9/17	3.8		
1/27	0.9	5/24	4.5	9/20	5.0		
2/1	0.8	6/7	7.1	9/30	4.2		
2/10	0.4	6/25	10	10/4	2.3		
2/17	0.2	6/28	3.5	10/18	2.6		
3/1	0.4	6/30	4	11/1	2.7		

Table 4. Total Coliform Bacteria per 100 ml in Influent and Effluent of Slow Sand Filter

Run.	Influent		Effluent					
			1st 2 days			Remainder		
	Mean	(#)*	Mean	(#)*	% Red.	Mean	(#)*	% Red.
A	2384	(10)	No data			159	(13)	93.3
B	0	(3)	2	(3)	-			
B (12/3-16/81)	9716	(4)				455	(4)	95.3
B (12/16-2/17/82)	2119	(15)				15	(15)	99.3
B (2/17-4/3)	500	(12)				1.6	(13)	99.7
C	737	(6)	1.7	(6)	99.8	1.0	(4)	99.9
D	47	(4)	8	(5)	83.0	1.5	(2)	96.8
E	112	(3)	12	(5)	89.3	3.7	(3)	96.7
F	191	(2)	18	(4)	90.6	0.5	(2)	99.7
G	74	(8)	1.4	(5)	98.1	0.4	(5)	99.5
H	42	(3)	2	(2)	95.2	Bad data		
I	121	(4)	10	(4)	91.7	0.5	(2)	99.6
J	215	(10)	18	(6)	91.6	0	(8)	100.0
K	1100	(8)	6	(5)	99.5	0.7	(7)	99.9

* Number of individual values used to calculate the mean value.

the primary goal was to evaluate the simplest systems for high quality surface waters. For that reason, the goal was to use only a single coagulant, either alum or a cationic polymer.* In some filter runs using alum as a coagulant, pH was lowered to about 6.8 with sulfuric acid to hopefully achieve better results. The acid was needed because of the relatively high alkalinity of the quarry water (150-200 mg/l as $CaCO_3$) which buffered the pH above 7.5 even after alum addition. Most upland waters of low alkalinity would have the pH reduced sufficiently by the alum alone so that this added complexity would not be necessary. Or, a cationic polymer could be used as a sole coagulant.

Also, in view of the small system emphasis, the range of filtration rates studied was limited to 6.6 to 16.1 m/h (2.7 to 6.6 gpm/sq ft). Higher rates were considered inappropriate for small systems.

Rapid mixing of the chemicals with the filter influent water was achieved by static mixers. No flocculation time was provided, but some detention after rapid mixing did exist in the influent hoses and in the water above the filter media. Because of the clarity of the raw water and the low doses of chemicals used, no visible floc particles were evident in the water above the filter media. Nevertheless, the evidence of destabilization was dramatized by the quality of the filtrate, and the abrupt loss of quality if the chemical feed was terminated either intentionally or accidentally.

The experimental results are summarized in Table 5 for all observation runs which were not disturbed by mechanical problems or abrupt changes in the raw water quality which required mid-run corrections to the chemical feed level.

Numerous additional filter runs were made between the runs shown in Table 5. These were made to select proper chemical dosages prior to an observation run. All runs shown in Table 5 were operated with optimum chemical dosage, at least to the best of our ability to select the dosage.

Influent and effluent turbidity data for the entire study period are available in Table 5. The lowest turbidity value given in Table 5 is the low value of the run before terminal breakthrough. As noted in Table 5, terminal breakthrough was not a common occurrence.

To round out the data presentation, the particle count results in the 7-12 µm size range and total coliform results are summarized in Tables 6 and 7 and the run length data in Table 8 for the entire study period.

In addition to the Tables, the data from typical runs will be presented in a series of figures, along with a discussion of seasonal trends and comparisons.

Results, Autumn 1981

In the fall of 1981, the quarry water was of reasonably good quality with low algal populations as evidenced by low chlorophyll measurements. Either alum with pH adjusted to 6.8, or Cat Floc T were quite adequate to achieve good filtrate turbidity. Typical results are

*Cat Floc T

Table 5. SUMMARY OF RAPID CONSTANT RATE FILTER RUNS

Run Number	Dates	Rate gpm/ s.f.	Approx raw NTU	Chemicals (mg/l) Alum	Polymer	Cl_2	Acid used	pH filtrate	Lowest filtrate NTU*	Breakthrough HL (cm)	Hrs.	At End HL (cm)	Hrs.
Alum Runs													
	(1981)												
A-1	10/20-22	2.8	4-6	7.1	---	--	yes	6.8	0.11	150	36	200	48
A-2	10/27-30	2.9	3-4	6.5	---	--	yes	6.3	0.14-0.09	none		195	76
A-3	11/3-5	2.9	2-6	6.4	---	--	yes	6.7	0.08	none		207	49
A-4	11/10-11	4.5	4-10	6.9	---	--	yes	6.8	0.12	none		208	31
A-5	11/17-18	4.7	3-4	7.0	---	--	yes	6.9	0.11	none		146	23
B-1	12/1-2	4.5	5-20	7.6	---	--	yes	6.8	0.14-0.08	none		186	31
Cat Floc T Runs													
B-2	12/8-12	2.8	3-12	--	0.76	--	no	8.5	0.10	none		193	95
B-3	12/14-15	4.7	5-6	--	0.70	--	no	8.6	0.16	none		207	26
	(1982)		Lake Frozen Over beginning, 12/18/81										
B-4	1/4-6	2.8	3-12	--	0.77	--	no	8.5-8.7	0.14	none		197	52
B-7	2/8-15	4.6	0.4-0.3	--	0.09	--	no	8.3	0.08	none		204	168
B-8	2/15-22	4.6	0.3 (130 hrs)-- 1.5 (36 hrs)--		0.09	--	no	8.3	0.10	none		208	168

Snow melt runoff begins - lake open around edges, 2/21/82

Table 5. SUMMARY OF RAPID CONSTANT RATE FILTER RUNS

Run Number	Dates (1982)	Rate gpm/s.f.	Approx. raw NTU	Chemicals (mg/l) Alum	Polymer	Cl_2	Acid used	pH filtrate	Lowest filtrate NTU*	Breakthrough HL (cm)	Breakthrough Hrs.	At End HL (cm)	At End Hrs.
Alum Runs													
B-10	2/24	4.6	4-5	10.3 & 12.3	--	--	yes	6.8	0.19	136	6.5	--	--
B-11	3/1-2	2.7	5-10	10.8	---	--	yes	6.8	0.15	135	22	154	26
Cat Floc T													
B-13	3/8-13	2.9	1-4	--	0.84	--	no	8.2	0.20	none		210	120
Lake ice cover completely gone, 3/28/82													
Alum Runs													
B-15	3/29-30	3.0	4-5	6.7	--	--	yes	6.8	0.14	none		130	26
C-1	4/13-14	3.0	4-8	8.1	--	--	yes	6.8	0.16	none		207	32
C-3	4/20-21	4.8	7-9	7.8	--	--	yes	7.6	0.24	130	5	210	13 est.
C-4a	4/26-27	4.2	6-7	12.1	--	--	yes	6.5	0.38	130 est.	7	170	11
Head loss recorders installed.													
Alum Runs													
E-1	6/1-2	3.0	5-6	7.4	--	--	yes	6.8	1.1	65 est.	4	158	22
Cat Floc T-1 Runs													
C-1	6/23-25	2.8	3-11	--	0.80	--	no	8.5	0.36	none		108	47

Table 5. SUMMARY OF RAPID CONSTANT RATE FILTER RUNS

Run Number	Dates (1982)	Rate gpm/s.f.	Approx. raw NTU	Chemicals (mg/l) Alum	Polymer	Cl_2	Acid used	pH filtrate	Lowest filtrate NTU*	Breakthrough HL (cm)	Hrs.	At End HL (cm)	Hrs.
Cat Floc T Runs													
G-2	6/28-30	2.7	1-30	--	0.67	--	no	8.4	0.40	none		56	49
Alum Plus Cl_2 (Cl_2 in some runs)													
H-1	7/20-21	3.0	13-15	19.8	--	5	no	7.9	0.40	160	12	210	16
H-2d	7/27-28	3.0	15->30	9.4	--	no	yes	7.0 est.	25-30	68	8	210	19
H-2f	7/30-31	3.0	15	12	--	5	yes	6.6	0.20	190	17	210	19
H-2h	8/1-2	3.4	9-16	10.3	--	5	yes	7.9	2.8	none		140	26
I-2	8/10-11	3.0	1.9-2.6	8.3	--	5	yes	7.8	0.25	none		110	24
I-3	8/11-12	3.0	2.0-2.4	8.3	--	3	yes	7.8	0.19	none		119	24
I-4	8/18	6.6	0.5-1.8	5.8	--	3	yes	7.9	0.13	none		210	11
I-5	8/19-20	6.6	0.9-1.6	5.6	--	3	yes	7.9 est.	0.42	none		114	23
Cat Floc T Runs													
I-6c	8/24-25	5.9	2-7	--	1.49	no	no	8.4 est.	0.42	none		133	22
I-6e	8/27-29	5.1	1.4-2.7	--	1.21	no	no	8.4	0.37	none		155	45

Table 5. SUMMARY OF RAPID CONSTANT RATE FILTER RUNS

Run Number	Dates (1982)	Rate gpm/ s.f.	Approx. raw NTU	Chemicals (mg/l) Alum	Polymer	Cl_2	Acid used	pH filtrate	Lowest filtrate NTU*	Breakthrough HL (cm)	Hrs.	At End HL (cm)	Hrs.
Alum Runs													
J-1	9/2	5.4	2-16	8.8	---	--	yes	7.8	0.20	187	10	206	11
J-2	9/2-3	5.5	3-8	8.1	---	--	yes	NR	0.22	none		200	10
Cat Floc T													
J-3	9/9-10	5.4	2-4	--	0.48	--	no	8.5	0.27	none		151	28
J-4	9/10-11	5.5	1-3	--	0.53 (3hr) 0.35 (31hr)	--	no	8.5	0.27	none		158	34
Alum Runs													
J-6	9/15-16	3.2	2-4	6.1	---	--	yes	7.8	0.17	none		136	24
J-7	9/16-17	3.1	2-5	6.1	---	--	yes	7.8	0.16	none		142	27
Cat Floc T													
J-8	9/22-26	3.1	2-4	--	0.58	--	no	8.4	0.25	none		201	95
J-9	9/27-10/2	3.2	1-3	--	0.45	--	no	8.4	0.22	none		161	122

*After initial improvement period when turbidity was stable at its lowest level and before terminal breakthrough (if it occurred).

Table 6. Mean Particle Removal by Rapid Filter in 7-12 mm Size Range.

Season	Run Dates	Chemical Used	Mean Influent No/ml	Mean % Particle Removal: First Hour %	(#)*	Remainder %	(#)*
	1981						
Fall	10/20-12/15	Alum	2320	97.6	(5)	98.8	(5)
		Cat Floc T	1170	91.9	(2)	96.7	(2)
	1982						
Winter (Ice Covered)	1/4-2/22	Cat Floc T	370	68.7	(3)	87.0	(3)
Snow Melt (Begins)	2/24-3/13	Alum	2190	97.0	(1)	99.0	(1)
		Cat Floc T	1620	97.0	(1)	98.0	(1)
Spring (Ice Gone)	3/29-4/21	Alum	2860	92.0	(3)	94.0	(3)
Summer	6/1-8/18	Alum	13040	85.0	(1)	99.0	(1)
		Cat Floc T & T-1	1350	89.0	(2)	85.5	(2)
		Alum & Cl_2	2730	86.0	(3)	92.0	(3)
Fall	9/2-10/2	Alum	1640	94	(2)	96.5	(2)
		Cat Floc T	340	87	(2)	87.5	(2)

* Number of mean filter run values used to calculate the mean % removal value.

shown in Figures 12 through 15 for one alum run and one Cat Floc T run.

The initial improvement period was pronounced in all runs, and most clearly defined by the continuous turbidity recording. It is clear that several hours are required for the filtrate to approach a steady quality.

Results, Winter 1981-82

With the formation of the ice cover on the quarry, the raw water quality got progressively better. Only Cat Floc T was used during the winter months, regrettably, in hindsight. Long runs with good filtrate were obtained with extremely low dosage of the polymer (0.09 mg/l). One typical run (B-7) is shown in Figures 16 and 17.

With this high quality raw water, the percentage removal of any of the 3 parameters was not as good as with poorer raw water, but the absolute levels of turbidity and particle count were excellent in spite of the lower fractional removals.

Comparing the winter and snow melt periods of Table 7, it is evident that alum appears superior to Cat Floc T in total coliform

Table 7. Mean Total Coliform Removal by Rapid Filter

Season	Run Dates	Chemical Used	Mean Influent No/100 ml	Percent Coliform Removal: First Hour %	(#)*	Remainder %	(#)*
	1981						
Fall	10/20-12/15	Alum	1300	90.5	(4)	91	(3)
		Cat Floc T	8200	88	(2)	96.5	(2)
	1982						
Winter (Ice Covered)	1/4-2/22	Cat Floc T	1500	77.7	(3)	89.7	(3)
Snow Melt (Begins)	2/24-3/13	Alum	1600	93	(1)	96	(1)
		Cat Floc T	640	72	(1)	89	(1)
Spring (Ice Gone)	3/29-4/21	Alum	350	79	(3)	91.3	(3)
Summer	6/1-6/30	Alum	90	80	(1)	86	(1)
		Cat Floc T & T-1	50	81.5	(2)	86	(2)
Fall	9/2-10/2	Alum	550	86.5	(2)	89	(2)
		Cat Floc T	170	70.5	(2)	86.5	(2)

* Number of mean filter run values used to calculate the mean % removal value.

removal, a trend which is also evident in Table 6 for particle removal efficiency.

Results, Spring 1982

With the onset of snow melt runoff into the quarry, but with ice cover still prevailing, the raw water immediately became more difficult to treat. Whereas filtrate turbidities of 0.10 to 0.15 were commonly achieved in the fall and winter (Table 5), it was not possible to achieve such results during this period of partial ice cover. Higher alum dosages were attempted to improve the filtrate (as in Runs B-10 and B-11) but this resulted in terminal breakthrough of turbidity with short filter cycles.

The use of Cat Floc T during this period generally eliminated the terminal breakthrough problem, but the best filtrate turbidity was about 0.2 TU as shown in Fig. 18 for Run B-13.

After the ice had completely left the quarry, the turbidity results with alum were different in shape with a shorter initial improvement period; but the minimum turbidity of 0.16 NTU was similar as shown in Fig. 19 for run C-1.

Table 8. Mean Run Lengths for Rapid Filter comparing Cat Floc T and Alum

Season	Run Dates	Chemical	Mean Run Length (Hrs) at 3 gpm/ft^2*	Mean Run Length (Hrs) at 5 $gpm\ ft^2$*
Fall '81	10/20-12/15	Alum	54 hrs	28 hrs
		Cat Floc T	95 "	26 "
Winter '81-'82 (ice covered)	1/4-2/22	Cat Floc T	52 "	168**
Snow Melt	2/24-3/13	Alum	22 "	6.5
		Cat Floc T	120 "	no data
Spring (No Ice)	3/29-4/21	Alum	29 "	6
Summer	6/1-8/18	Alum	4 "	no data
		Cat Floc T & Tl	48 "	no data
		Alum + Cl_2	21 "	17
Fall	9/2-10/2	Alum	26 "	10
		Cat Floc T	109 "	31

*Nominal rates, actual rates somewhat higher or lower as shown in Table 5
**Mid-winter with extremely good raw water (Runs B-7 & B-8)

Results, Spring and Summer 1982

The first major algae bloom occurred in late April and resulted in short cycles to breakthrough as shown in Fig. 19 for Run C-3.

These difficult treatment conditions persisted to varying degrees throughout the summer with the worst runs observed in late May, early June and late July as shown in Table 5. In run E-1 while using alum, the best filtrate turbidity achieved was 1.1 NTU and terminal breakthrough began in 4 hours at 65 cm head loss. Two different Cat Floc polymers were used in Runs G-1 and G-2, and the best filtrate turbidity of 0.36 and 0.40 NTU, respectively, but run length was better at 2 days.

In late July during a severe algae bloom, it became impossible to produce acceptable filtrate without the use of chlorine ahead of the filters as is evident by comparing Runs H-1 and H-2f with Cl_2 and Run H-2 without Cl_2. These runs using alum plus Cl_2 were only marginally acceptable because of short run lengths. Of course, prechlorination or preozonation are common practice in direct filtration plants. We avoided the use of prechlorination because of our desire to use bacterial parameters of removal efficiency. No bacterial data collection was attempted during the periods of prechlorination.

Results, Autumn 1982

After July, the quarry water improved dramatically, achieving the lowest raw water turbidities of the year, except during winter ice cover. In spite of the apparent good raw water during August and September of 1982, it was impossible to achieve filtrate turbidity levels as low as in the fall of 1981. During the J series Runs in September 1982, low turbidities of 0.15 to 0.25 were achieved, with alum being slightly superior to Cat Floc T. The same trend is evident in the particle count data and total coliform data (Tables 6 and 7, respectively).

CONCLUSIONS

The following conclusions can be drawn from the foregoing data presentation.

Slow Sand Filtration Conclusions

1. The filtrate quality was somewhat inferior for one to 2 days at the beginning of each filter run when compared with the quality for the remainder of the filter run. A period of filtering to waste of this duration is appropriate where Giardia cysts are of concern.

2. There was a gradual improvement in the filter performance by all three parameters (turbidity, particle count and total coliform bacteria) over the first 5 runs, a period of about 8 months. Subsequently, 7-12 μm particle removal was always better than 97% and coliform removal was better than 99%, reaching 100% in one run (Tables 3 and 4).

3. Filter run length was generally rather short, being less than 39 days in 9 out of 10 runs, all of which were terminated by a steeply accelerating head loss curve. Only under winter conditions when algal populations were reduced was a long run of 123 days achieved. During serious algal blooms, runs were as short as 9 days. Increasing available head loss would not increase these run lengths appreciably because of the exponentially upward head loss curves.

4. Turbidity alone is not an adequate predictor of the probable run length which can be expected. Algal enumeration or a surrogate measure of algal population, such as chlorophyll, are essential parameters to judge the acceptability of a raw water for slow sand filtration.

5. There was no evidence that the filter was clogging in depth to any substantial degree. The initial head loss at the beginning of each cycle reached a steady level after the first two runs, and did not get progressively higher. This absence of depth clogging was also confirmed by scanning electron microscope examination of the sand at several depths at the end of the project.

Rapid Filtration Conclusions

The following conclusions are based on the direct, in-line, filtration studies reported herein, using alum or cationic polymer as a coagulant.

1. An initial period of poorer filtrate quality existed in all filter runs as evidenced by turbidity, 7-12 μm particle count data and total coliform data. The period of initial improvement may last several hours in some cases, although the worst effects are over in one hour. Thus, where Giardia cysts are of concern, a filtering to waste period of one hour is appropriate.

2. Use of cationic polymer resulted in substantially longer filter cycles than alum, but a slightly inferior filter by all three parameters. Run length and filtrate quality comparisons are clouded by the fact that the comparison runs were sequential rather than in parallel.

3. Selecting the optimum dosage of cationic polymer was more difficult than selecting the optimum dosage of alum. With a variable raw water quality, it is more difficult to pace the optimum dosage of polymer to the water quality and overdosage or underdosage can easily occur.

4. Alum dosages between 5 and 10 mg/l (as $Al_2(SO_4)_3 \cdot 18H_2O$) were capable of treating raw waters with turbidities as high as 20 NTU and produce acceptable filtrate well below 1 NTU and reasonable filter run length when serious algal blooms were not in progress.

5. During periods of heavy blue-green algae population with turbidities of 15 in the raw water, prechlorination was essential to the reasonable success of the direct, in-line, filtration process. Alum dosages up to 20 mg/l were used with filter cycles as short as 11 hours at 3 gpm/sq ft. Without prechlorination, filtrate quality of less than 1 NTU could not be assured.

6. The percent removal of 7-12 μm particles generally exceeded the percent removal of total coliform bacteria. This might be expected because the greater size of the 7-12 μm particle compared with typical bacterial size.

7. The percent removal of 7-12 μm particles after the first hour of the cycle was above 85% in all seasons (Table 6) exceeded 90% in 8 of 11 cases and 95% in 6 of 11 cases in Table 6.

8. The percent removal of total coliform bacteria was greater than 86% in all seasons (Table 7), greater than 90% in 4 of 10 cases, and greater than 95% in 2 of 10 cases in Table 7.

9. Selection of the optimum dose of coagulant for direct, in-line filtration was not an easy task because of the variability of raw water quality. Overdosing with alum can be detrimental in causing excessive head loss and early breakthrough. Overdosing or underdosing with cationic polymer results in poorer filtrate quality throughout the run.

10. Selection of optimum dose of cationic polymer using pilot scale equipment and continuous recording turbidimeters can be assisted by briefly halting the polymer feed (about 20-30 minutes) and observing the turbidity response. If the prior dosage was too high, the filtrate will improve briefly as the dosage residual in the filter diminishes, and then deteriorate as the residual disappears. If the prior dosage was too low, the filtrate will begin to deteriorate immediately upon cessation of polymer feed.

Conclusions Related to Slow and Rapid Filtration

1. Where simple operation is of substantial importance as in small water supply systems, slow sand filters are superior. However, the raw water must be of consistent high quality and low in algae to avoid excessively short cycles.

2. Both systems require a filtering to waste period where *Giardia* cysts are of concern. Therefore, a minimum of two filters is desirable even for the smallest system. This will also allow for periodic filter maintenance, and for slow sand filter draining and scraping after each cycle.

3. The influent flow splitting system used in the pilot plant of this study is an ideally simple system which would be appropriate to both rapid or slow sand filter plants for small installations. This arrangement (i) eliminates the possibility of sudden rate changes, (ii) eliminates the possibility of negative head and consequent air binding, (iii) eliminates the need for rate control equipment or head loss equipment, and (iv) it can easily be made fail safe with a high water overflow to waste, and a turbidity monitoring and automatic shut down capability.

4. A good parallelism was evident for the three parameters of filtrate quality used in this study, namely turbidity, particle count and total coliform count.

REFERENCES

1. Amirtharajah, A. and D. P. Wetstein. Initial degradation of effluent quality during filtraiton. Journ. Amer. Water Works Assoc. Vol. 72: 518-524, 1980.

2. Cleasby, J. L. and E. R. Baumann. Selection of sand filtration rates. Jour. Amer. Water Works Assoc. Vol. 54: 579-602, 1962.

3. Cleasby, J. L., M. M. Williamson, and E. R. Baumann. Effect of rate changes on filtered water quality. Jour. Amer. Water Works Assoc. Vol. 55: 869-880, July, 1963.

4. Craun, G. F. Waterborne outbreaks of Giardiasis, 1979. In Jakubowski, W. and J. C. Hoff (eds.) Proc. National Symposium on Waterborne Transmission of Giardiasis. USEPA, Cincinnatti, Ohio, Sept. 18-20, 1978. EPA-600/9-79-001.

5. Craun, G. F. Waterborne outbreaks in the United States. Jour. Amer. Water Works 73: 360-369, July 1981.

6. DiBernardo, L. and J. L. Cleasby. Declining rate versus constant rate filtration. Journ. Environ. Eng. Div. ASCE. 106: EE6, 1023-1041, Dec. 1980.

7. Ellms, J. W. Water Purification. McGraw Hill Book Co. Inc., New York, 1917.

8. Kirner, J. C., J. D. Littler and L. A. Angelo. A waterborne outbreak of Giardiasis in Camus, Wash. Jour. Amer. Water Works, 70: 41-45, Jan. 1978.

9. Lippy, E. C. Tracing a Giardiasis outbreak at Berlin, N. H. Jour. Amer. Water Works 70: 512-520, 1978.

10. Lippy, E. C. Waterborne disease: Occurrence is on the Upswing. Jour. Amer. Water Works 73:57-62, Jan. 1981.

11. Logsdon, G. S. et al. Alternative filtration methods for removal of Giardia cysts and cyst models. Jour. Amer. Water Works 73: 111-118, Feb. 1981.

12. Microbiological Methods for Monitoring the Environment, Water and Wastes. (EPA 600/8-78-017, Dec. 1978).

13. Standard Methods for Examination of Water, 15th Edition, American Public Health Association: Washington, D. C. 1980.

14. Recommended Standards for Water Works, Great Lakes-Upper Mississippi River Board of State Sanitary Engineers. 1976 Edition.

15. Tuepker, J. L. and C. A. Buescher, Jr. Operation and maintenance of rapid sand mixed-media filters in a lime softening plant. Jour. Amer. Water Works Assoc. 60: 1377, 1969.

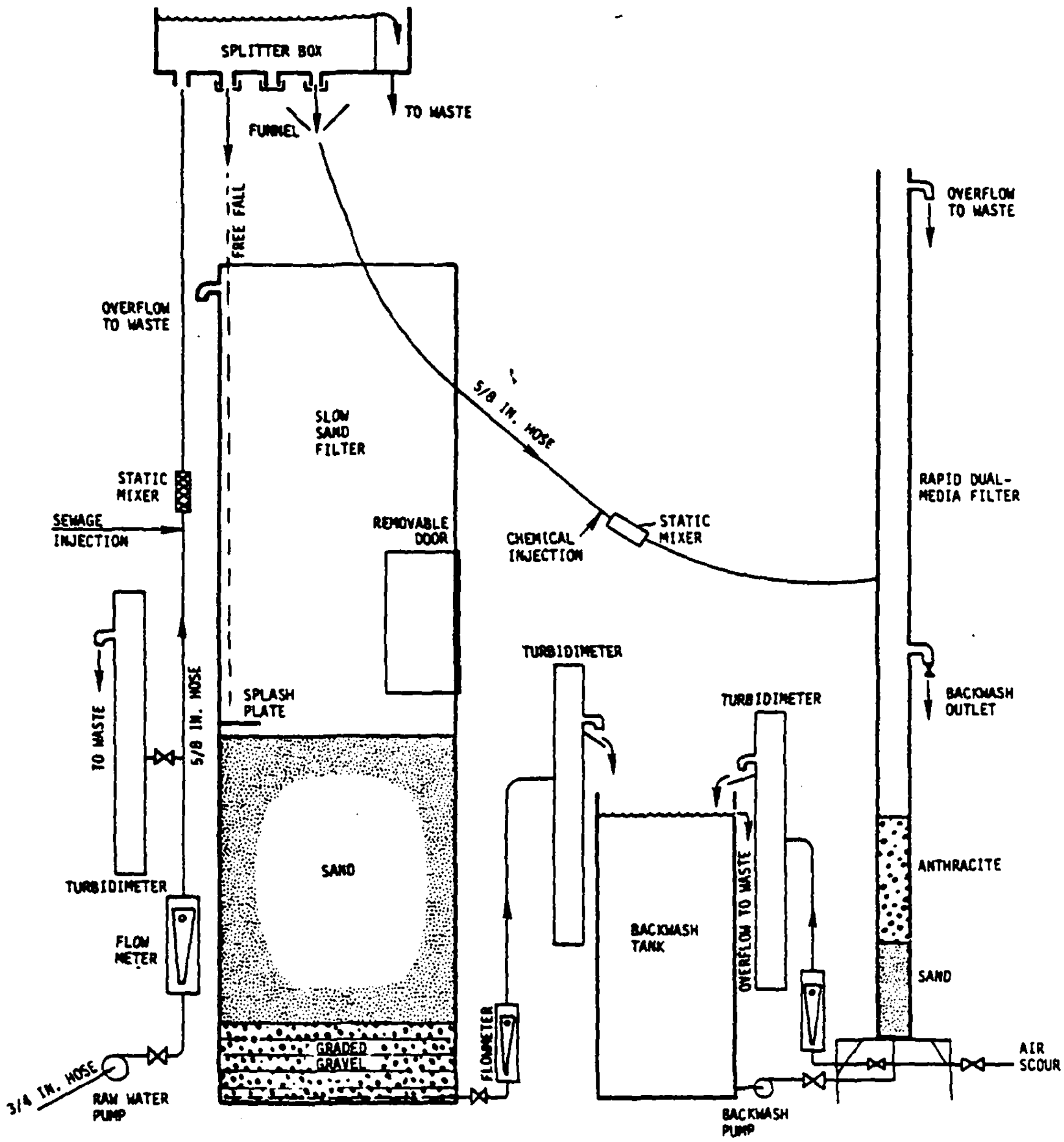

Fig. 1. Pilot plant schematic showing slow sand filter and rapid, dual-media filter.

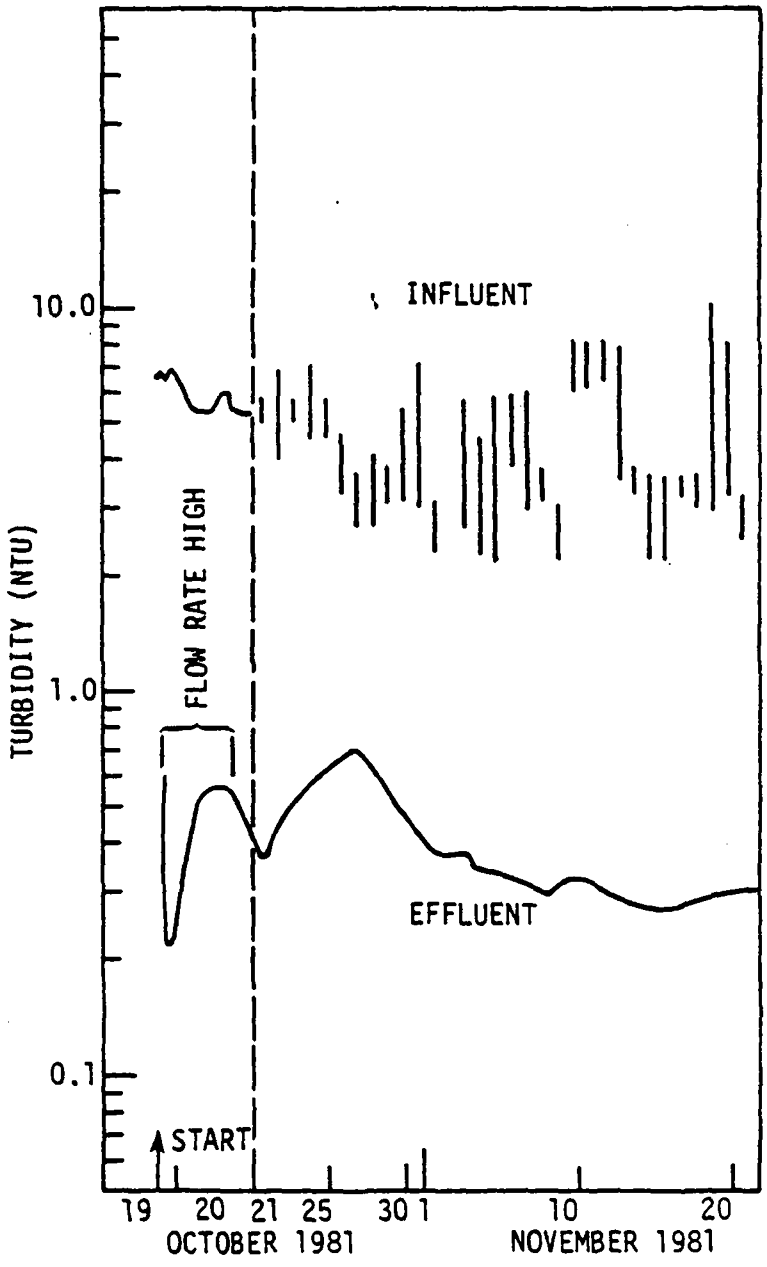

Fig. 2. Turbidity of influent and slow sand filter effluent during Run A. Influent bars show range of values recorded each day.

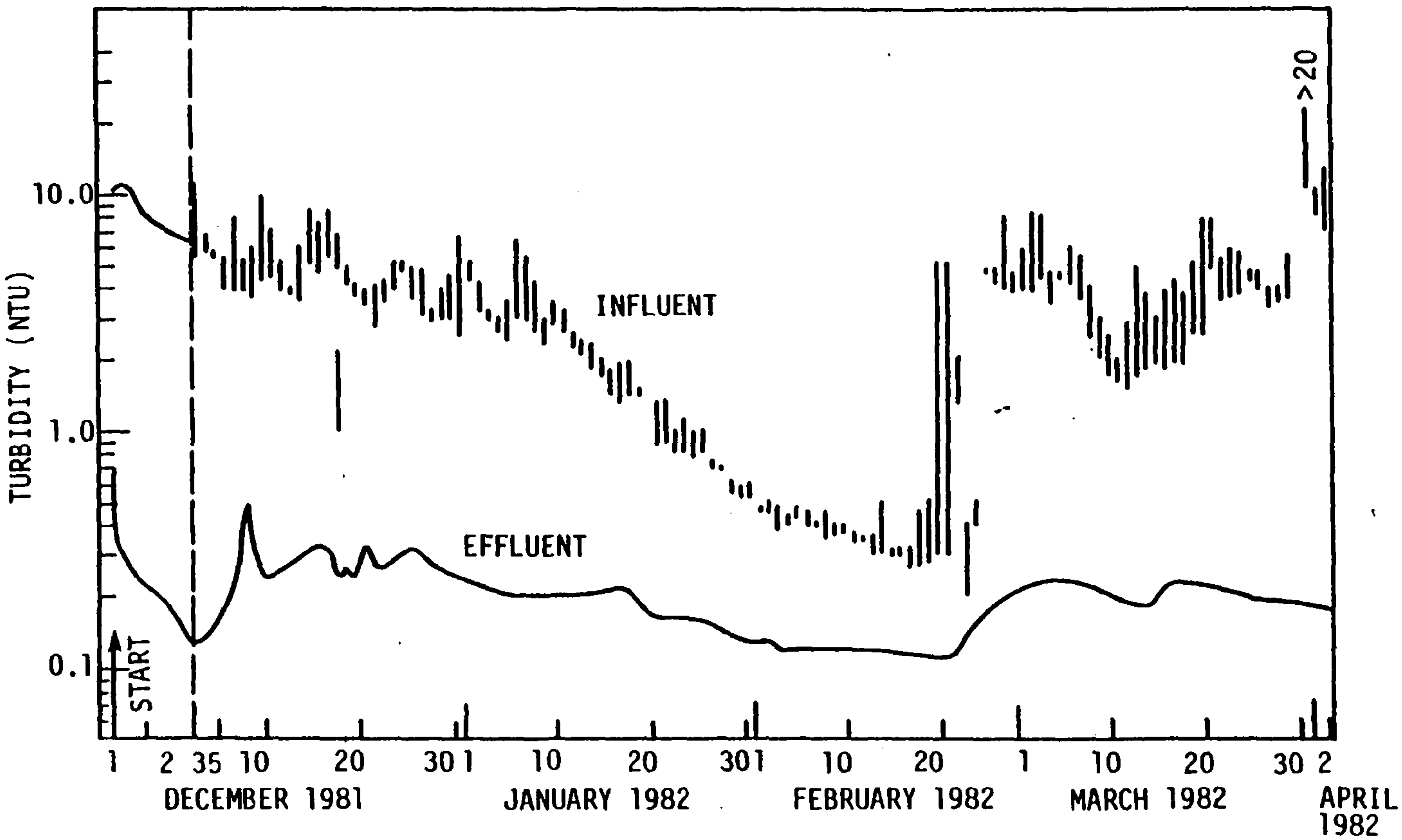

Fig. 3. Turbidity of influent and slow sand filter effluent during Run B. Influent bars show range of values recorded each day.

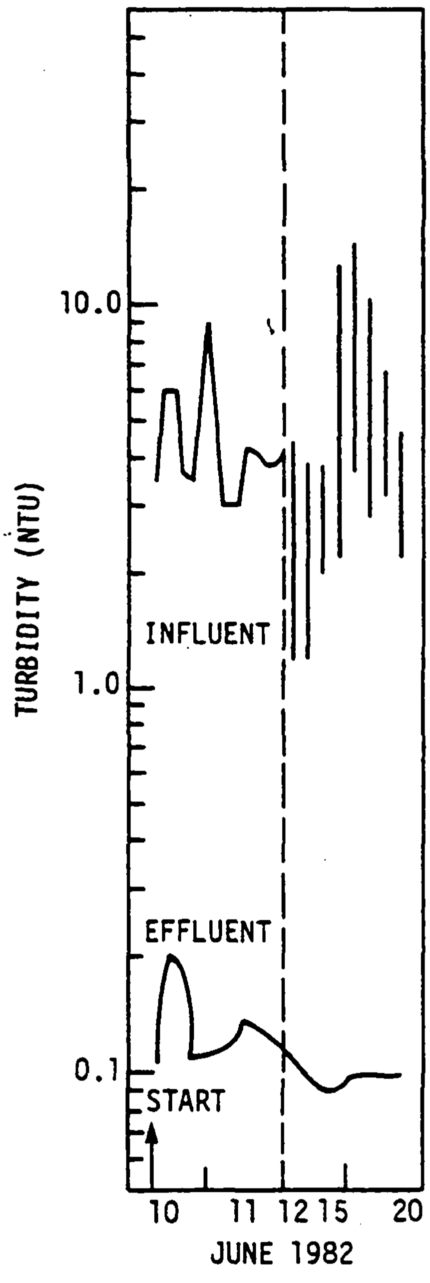

Fig. 4. Turbidity of influent and slow sand filter effluent during Run F. Influent bars show range of values recorded each day.

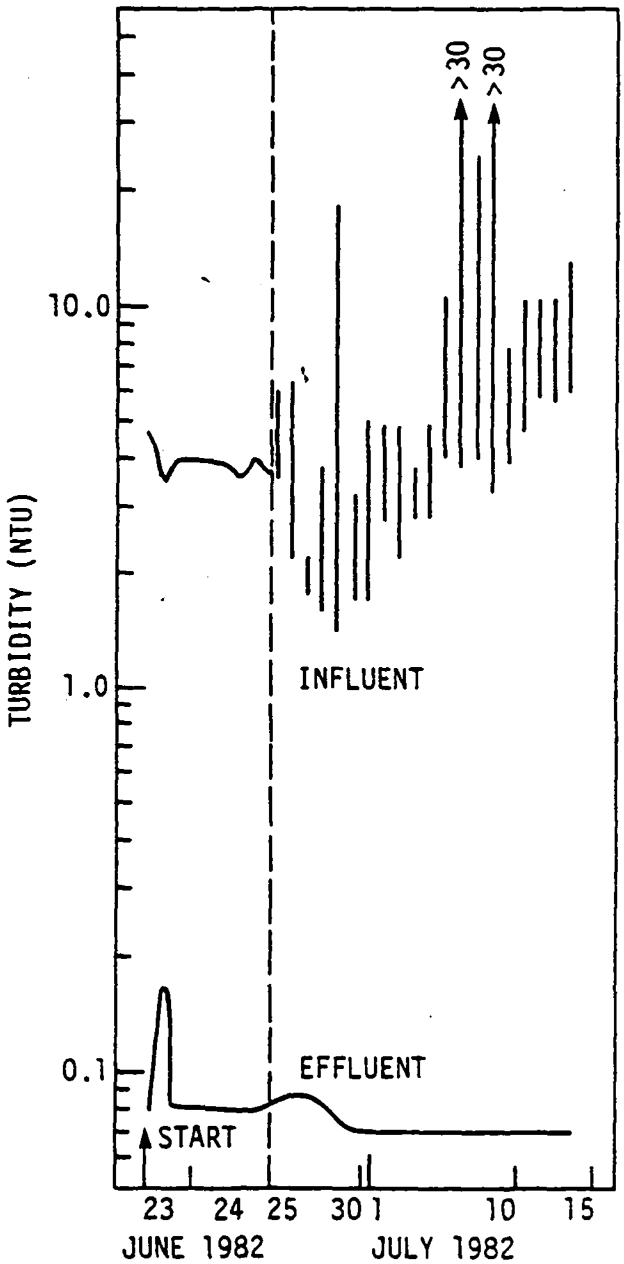

Fig. 5. Turbidity of influent and slow sand filter effluent during Run G. Influent bars show range of values recorded each day.

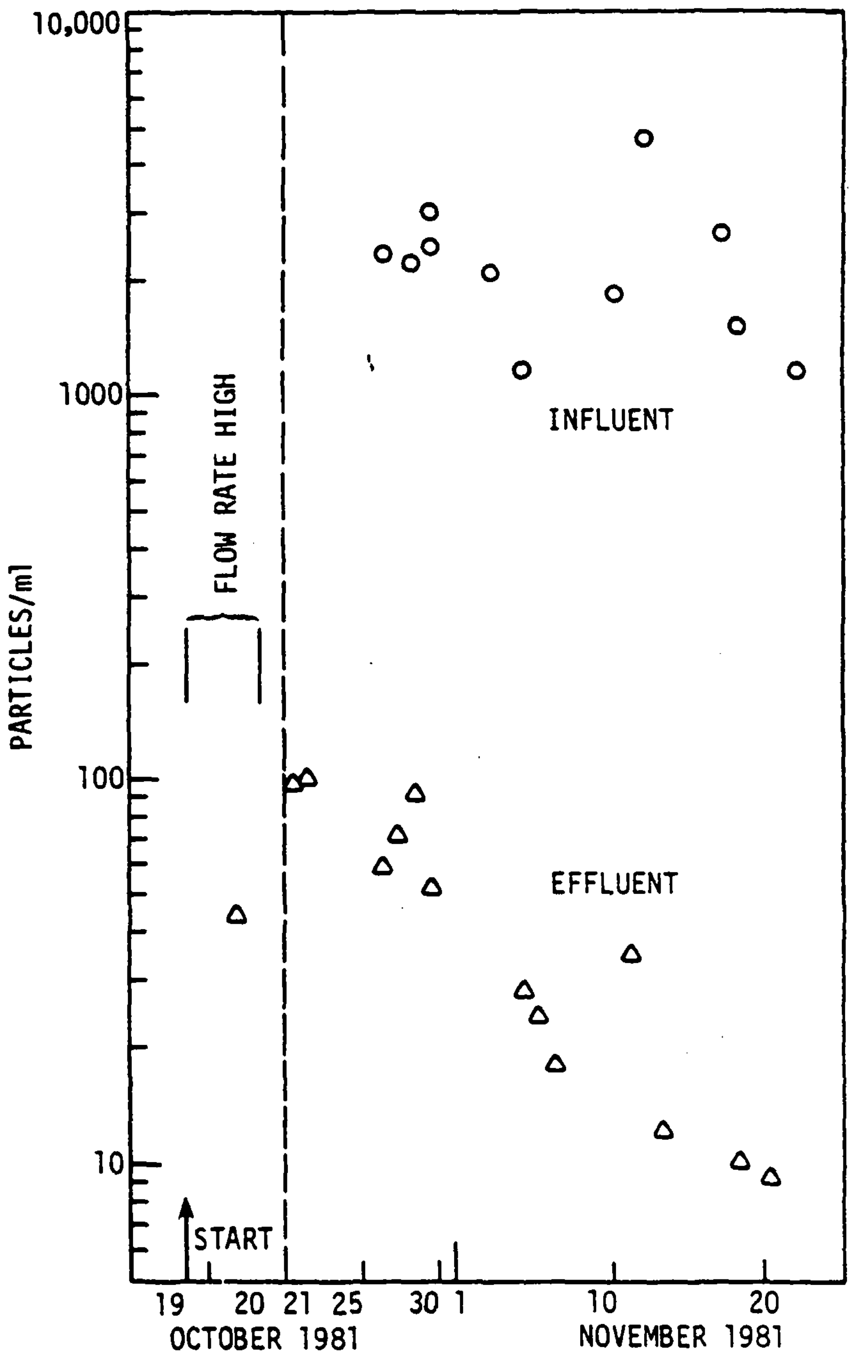

Fig. 6. Particle count in channels 7-9 (7 to 12 μm nominally) in the influent and effluent of slow sand filter during Run A.

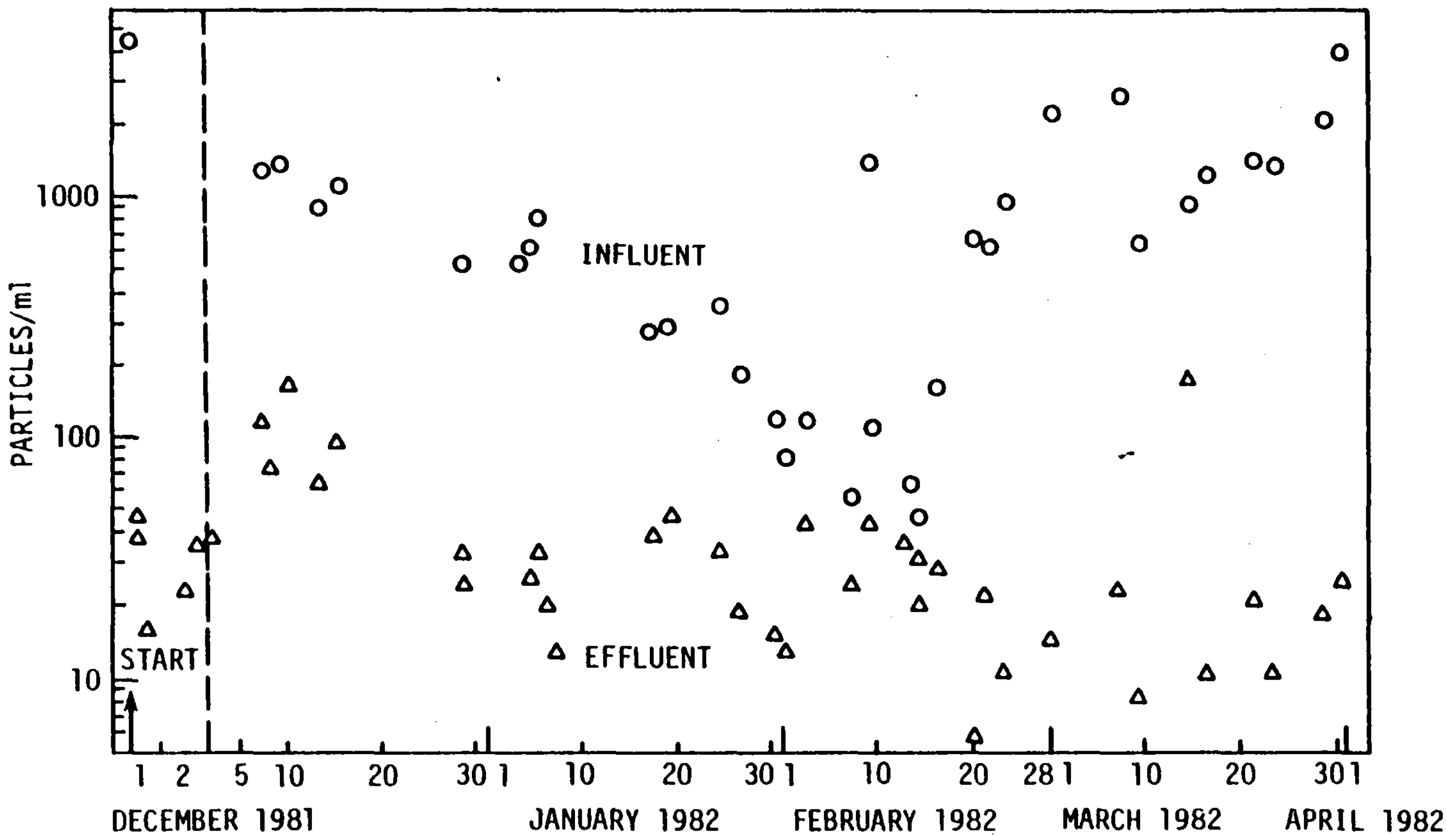

Fig. 7. Particle count in channels 7-9 (7 to 12 μm nominally) in the influent and effluent of slow sand filter during Run B.

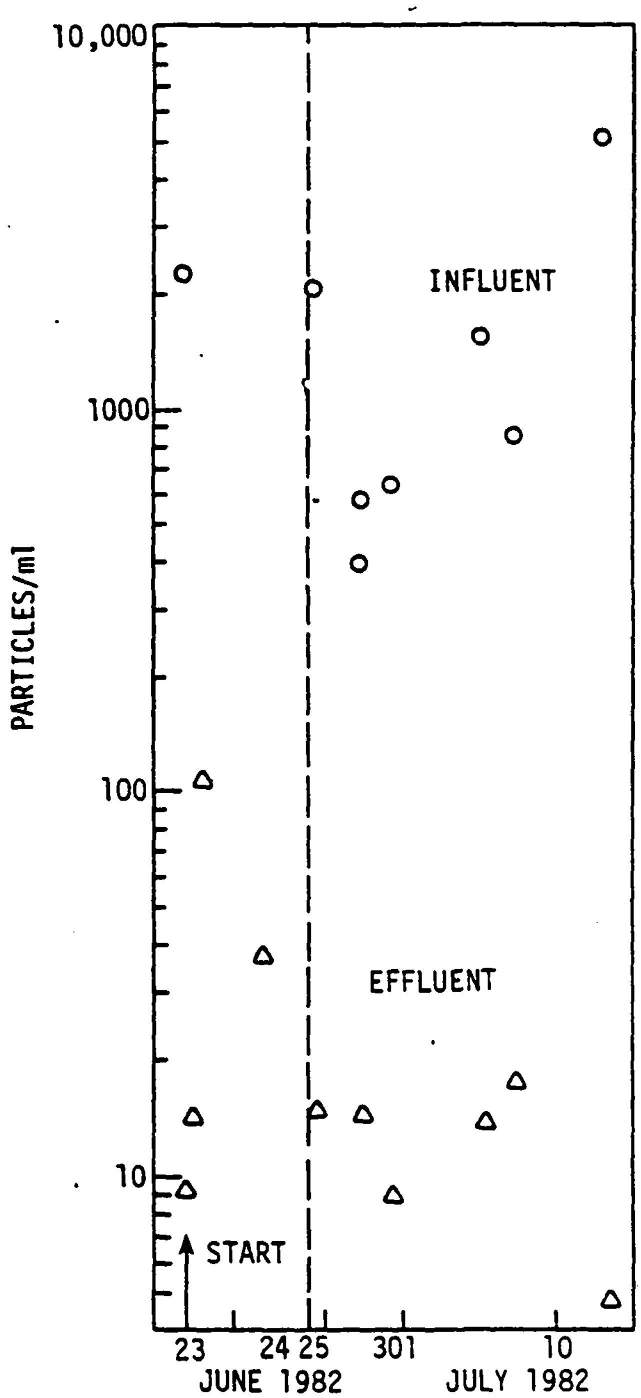

Fig. 8. Particle count in channels 7-9 (7 to 12 μm nominally) in the influent and effluent of slow sand filter during Run G.

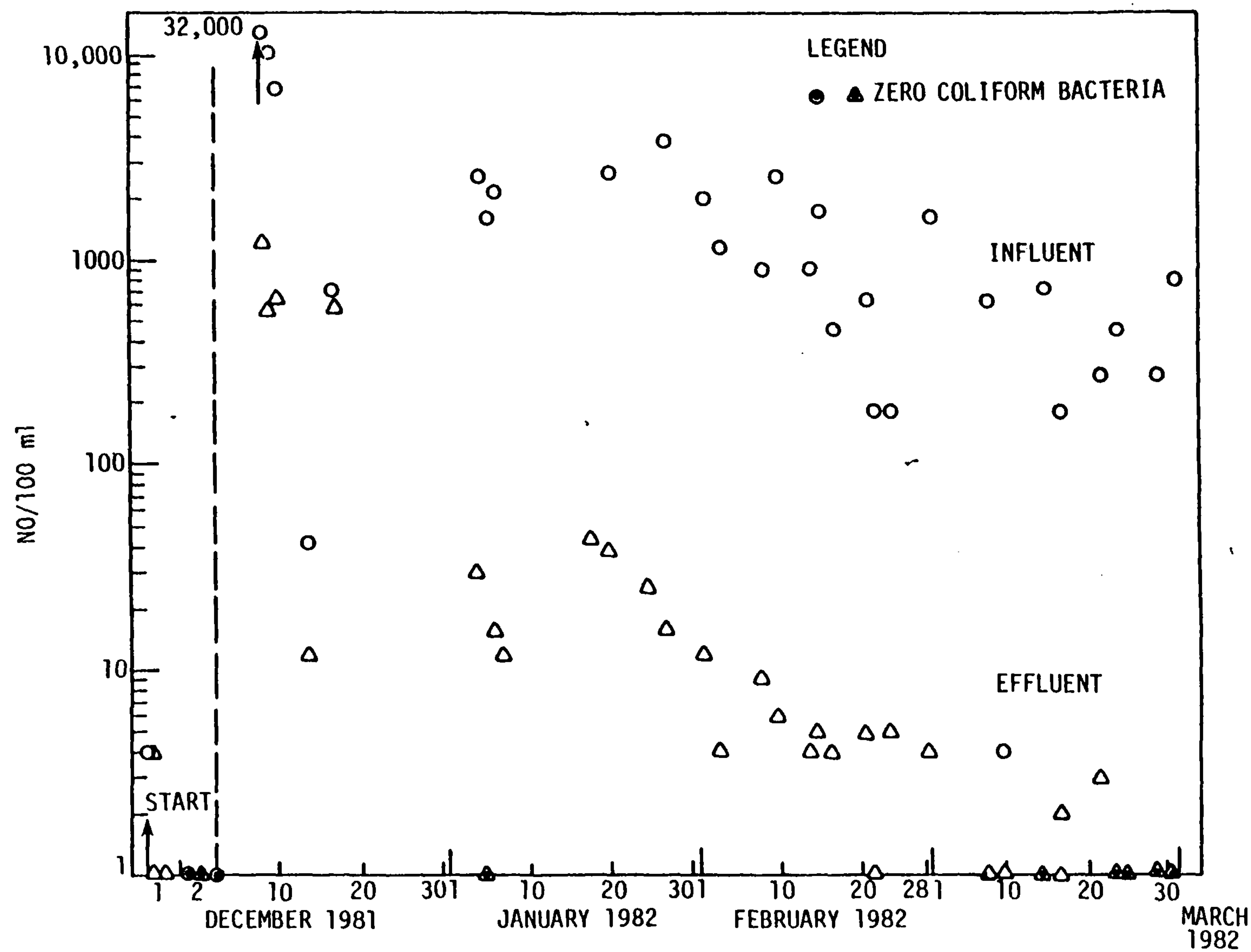

Fig. 9. Total coliform bacteria of influent and effluent of slow sand filter during Run B. Samples reported with zero coliform bacteria are plotted at the level of 1/100 ml.

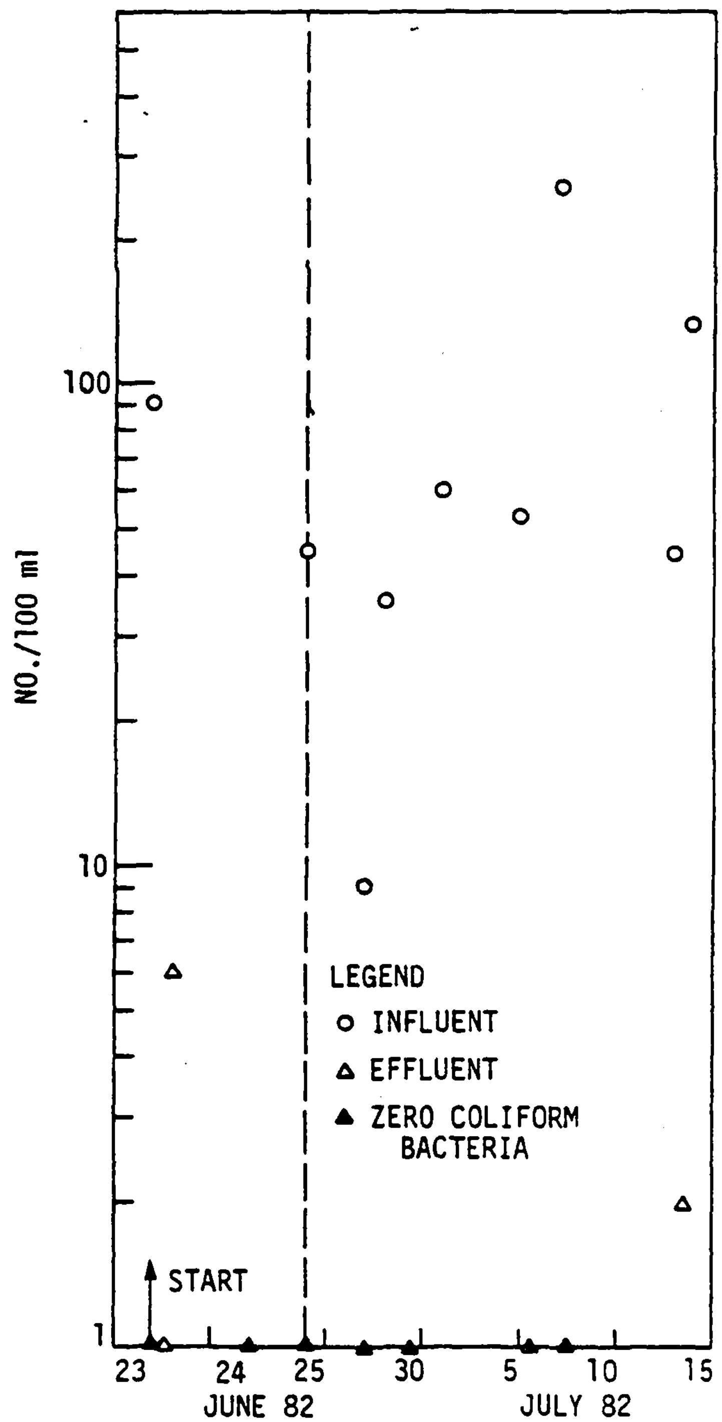

Fig. 10. Total coliform bacteria of influent and effluent of slow sand filter during Run G. Samples reported with zero coliform bacteria are plotted at the level of 1/100 ml.

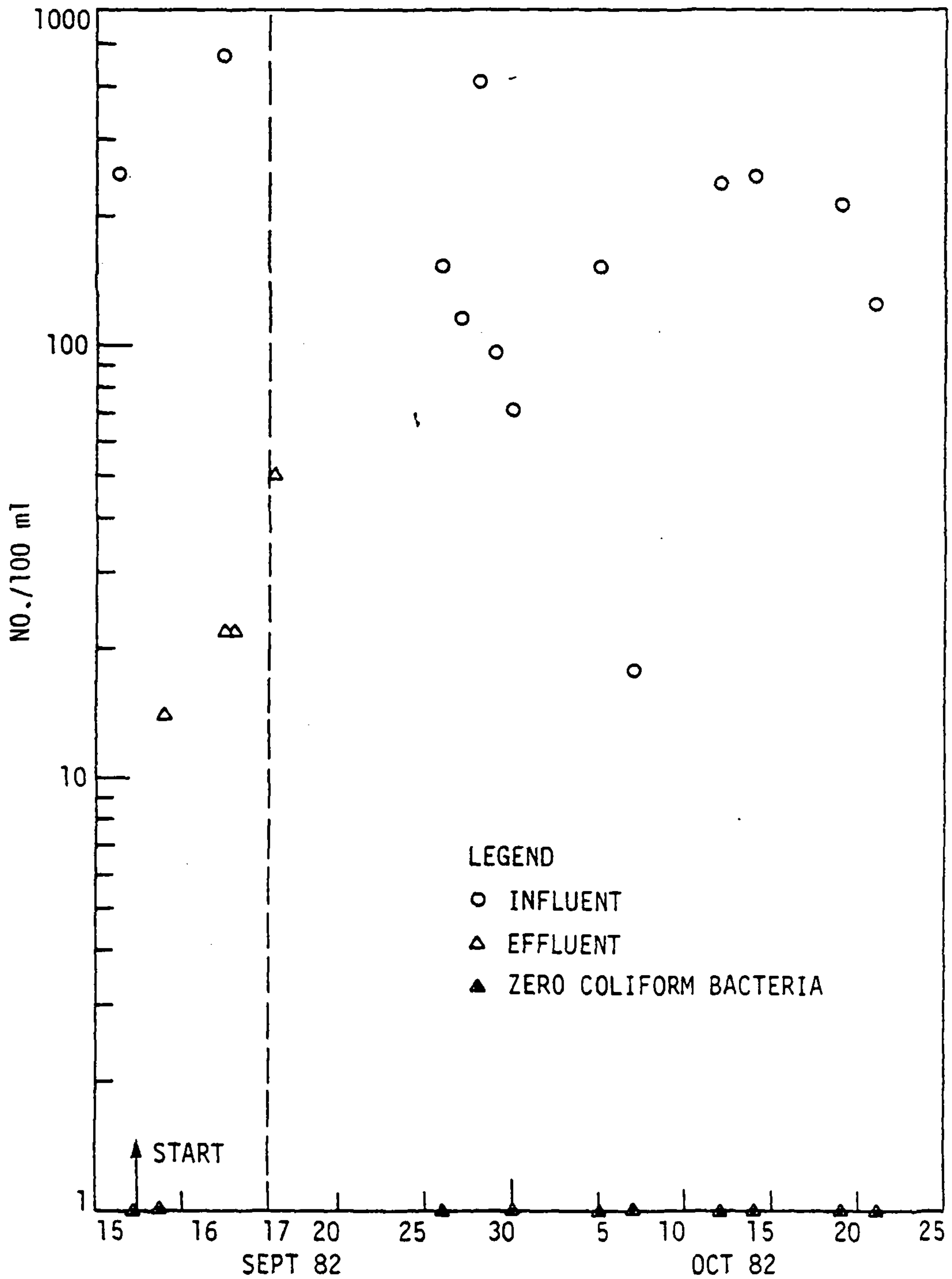

Fig. 11. Total coliform bacteria of influent and effluent of slow sand filter during Run J. Samples reported with zero coliform bacteria are plotted at the level of 1/100 ml.

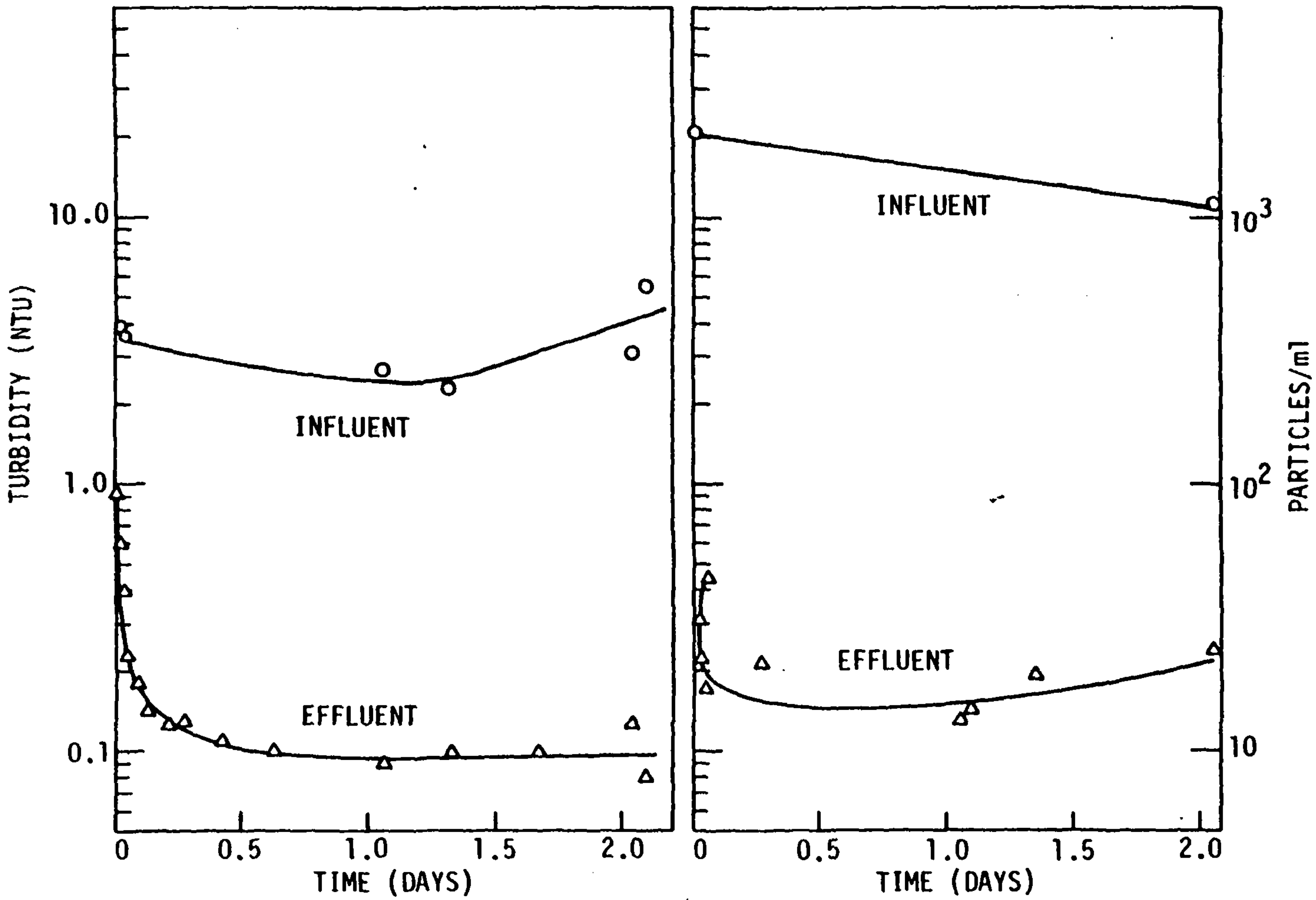

Fig. 12. Turbidity and 6.9-12.5 μm particle count during Run A-3 at 2.9 gpm/ft^2 using alum coagulant.

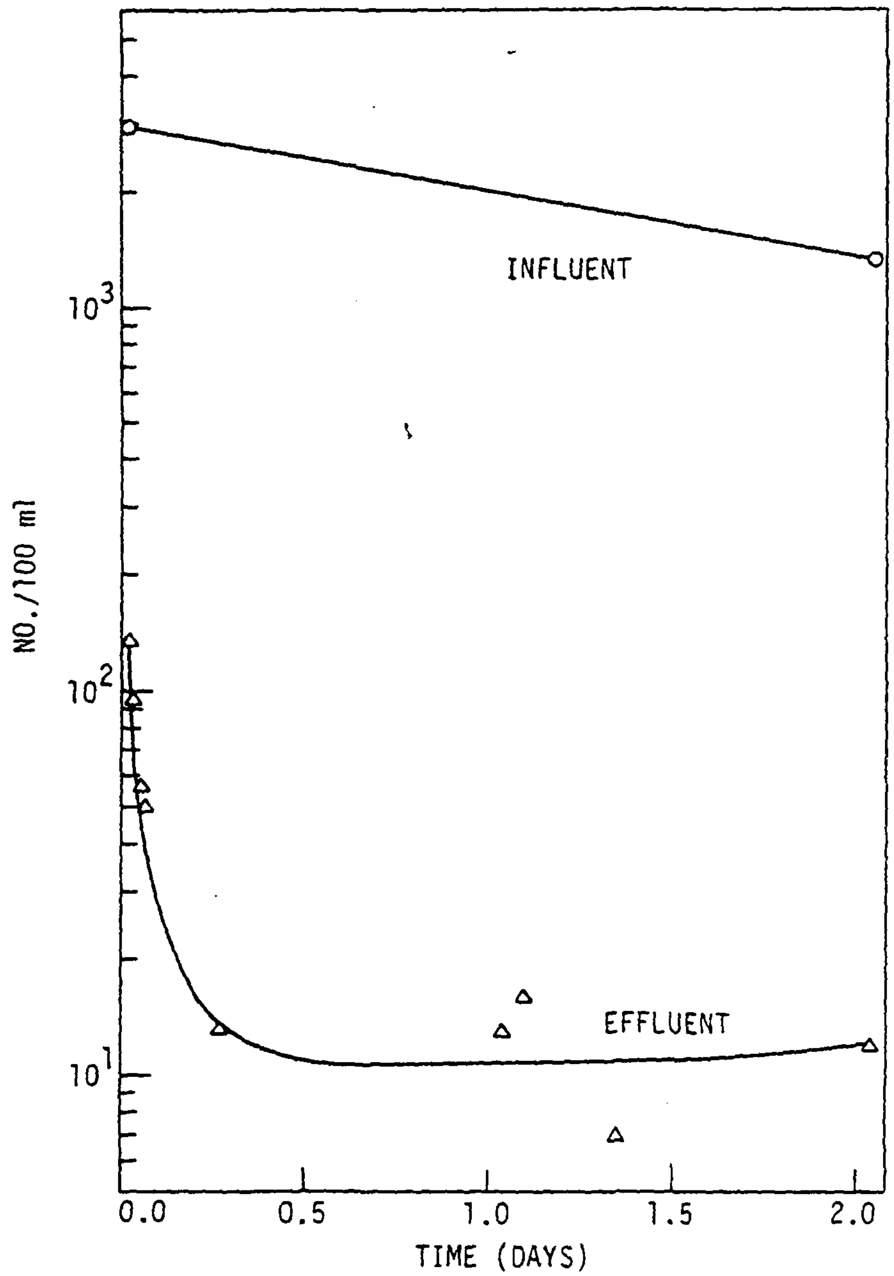

Fig. 13. Total coliform bacteria during Run A-3 at 2.9 gpm/ft^2 using alum coagulant.

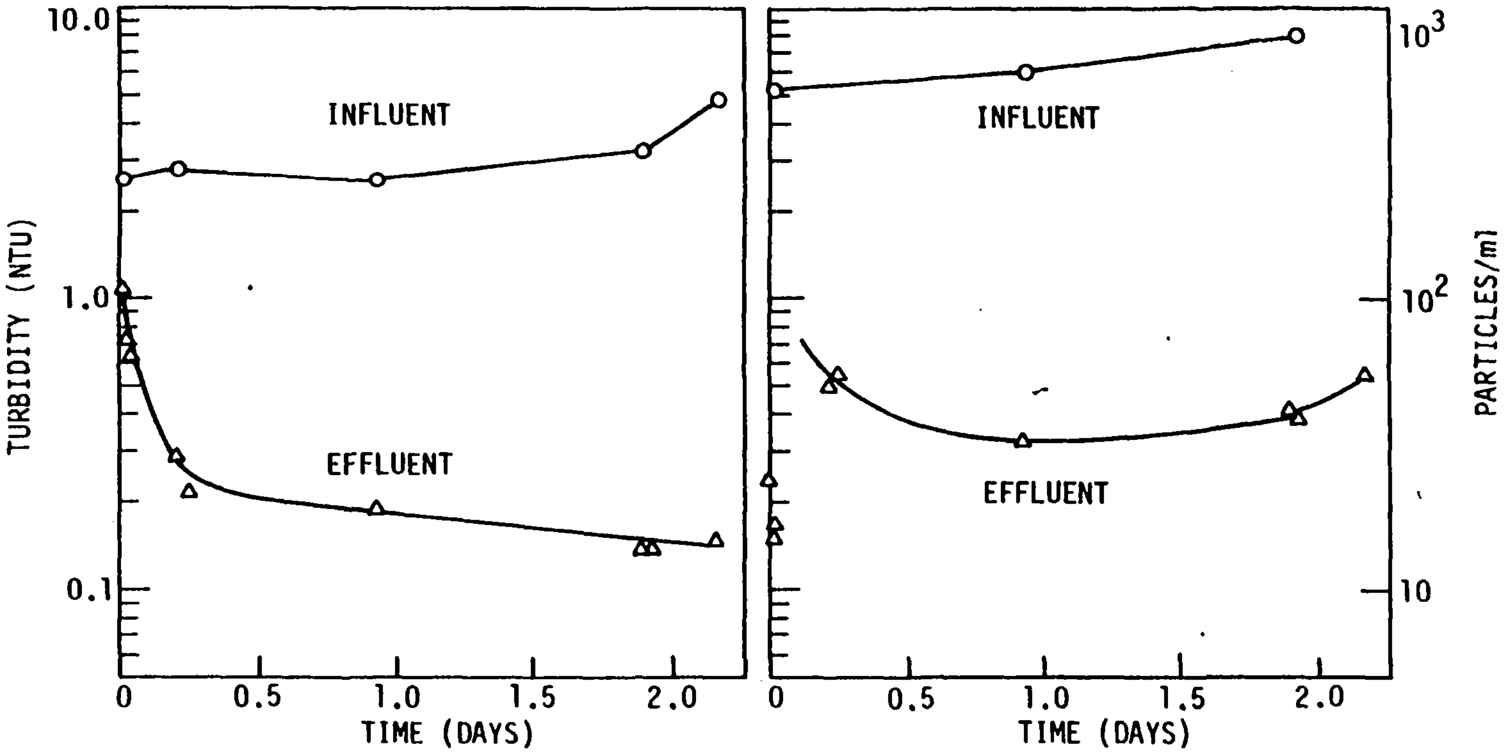

Fig. 14. Turbidity and 6.9-12.5 μm particle count during Run B-4 at 2.8 gpm/ft^2 using Cat Floc T coagulant.

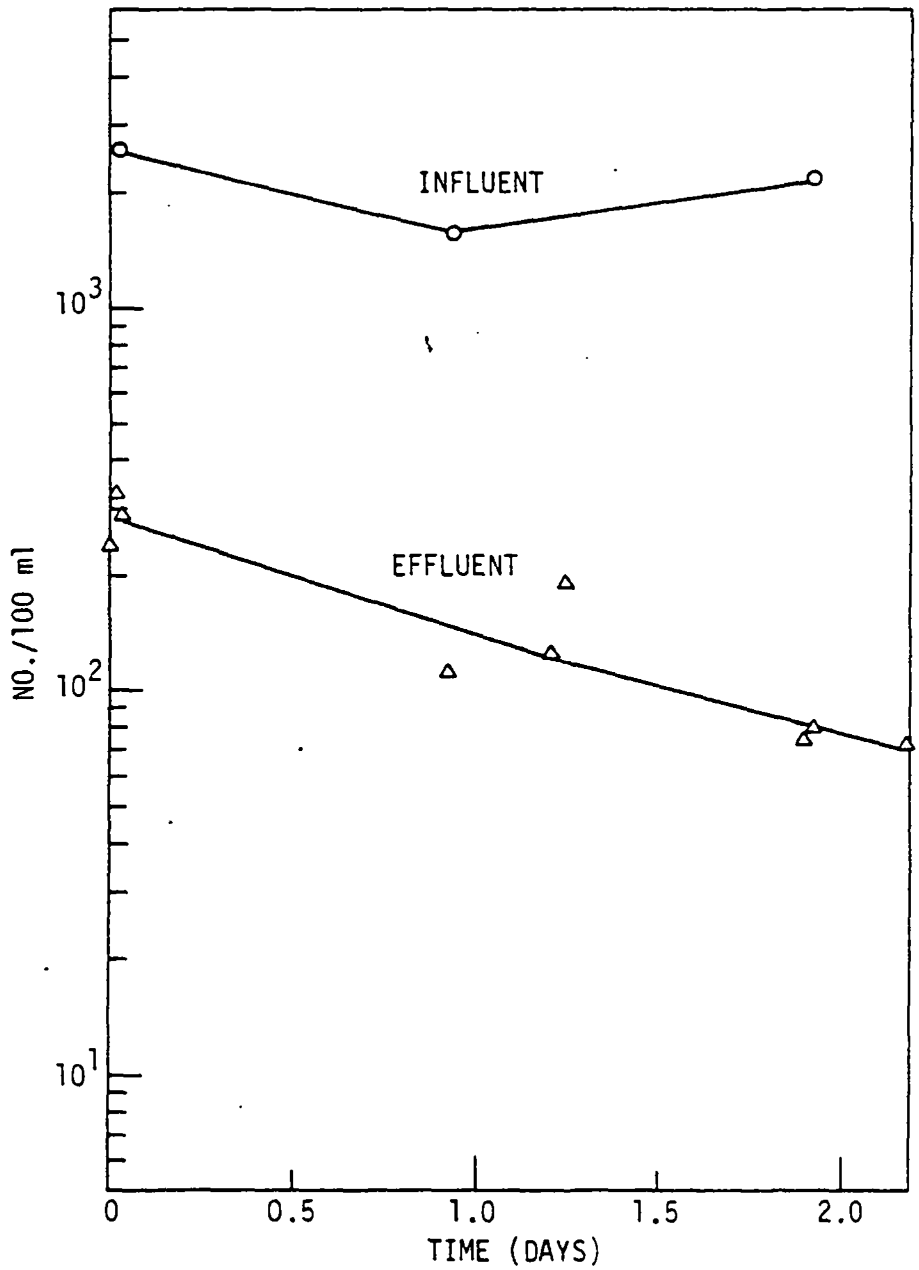

Fig. 15. Total coliform bacteria during Run B-4 at 2.8 gpm/ft^2 using Cat Floc T coagulant.

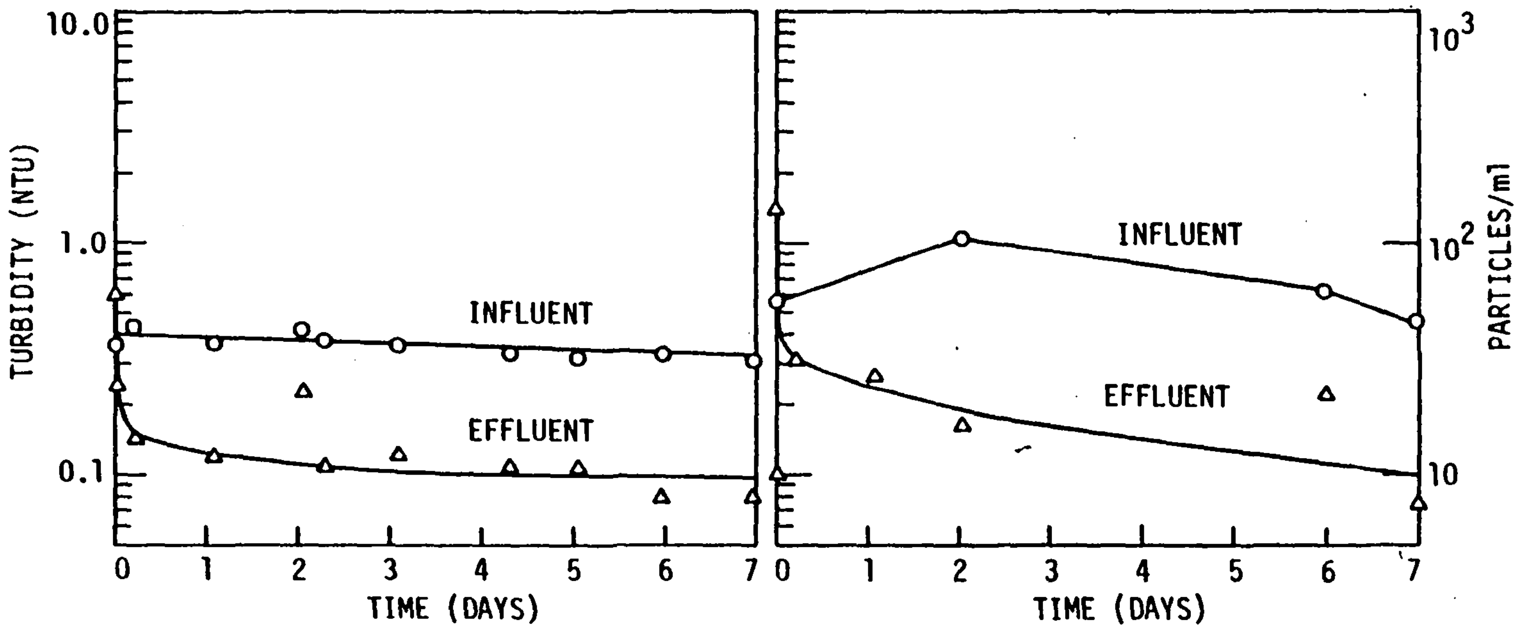

Fig. 16. Turbidity and 7-12 μm particle count during Run B-7 at 4.6 gpm/ft^2 using Cat Floc T coagulant under winter ice at 2 ^oC.

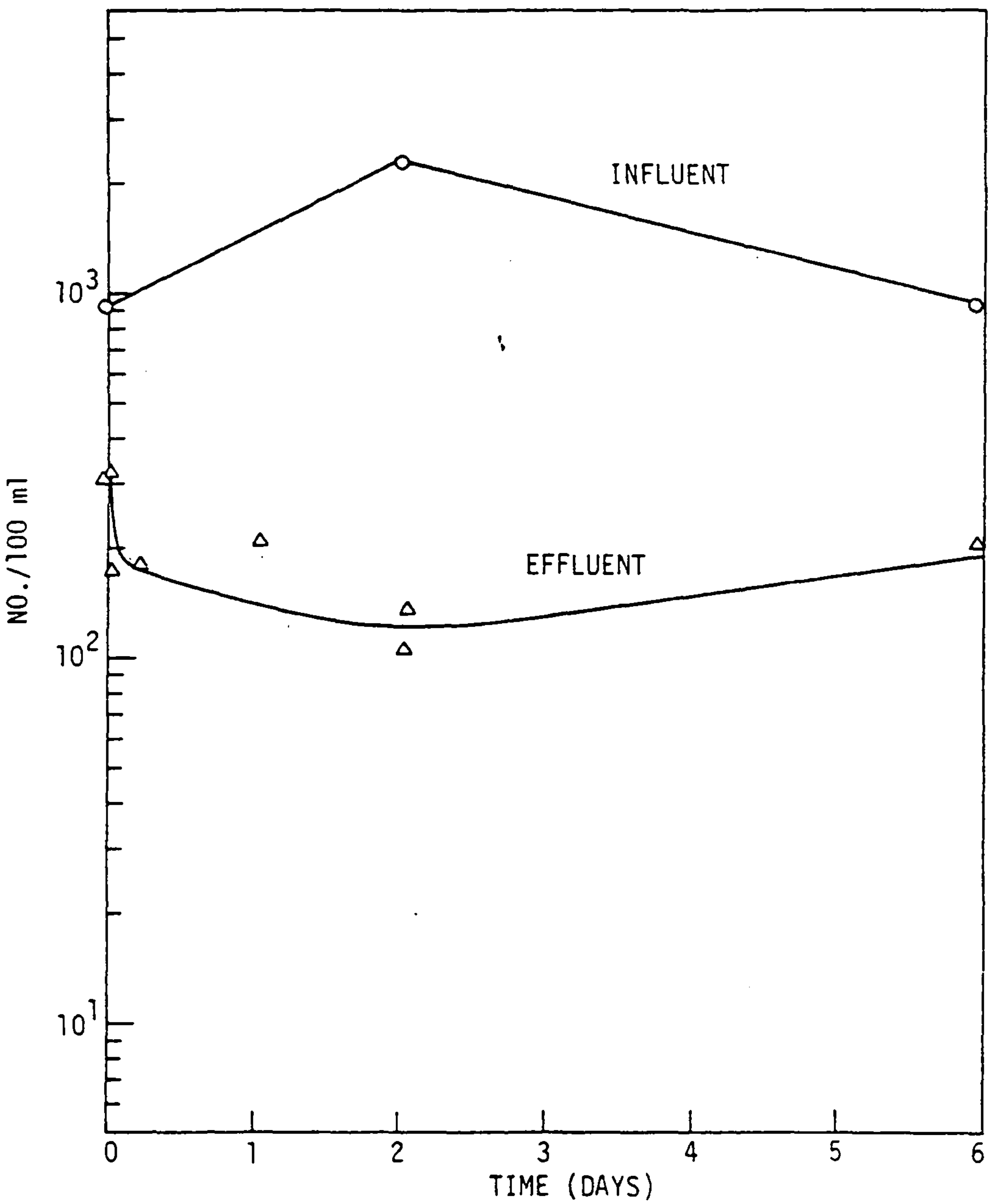

Fig. 17. Total coliform bacteria during Run B-7 at 4.6 gpm/ft^2 using Cat Floc T coagulant.

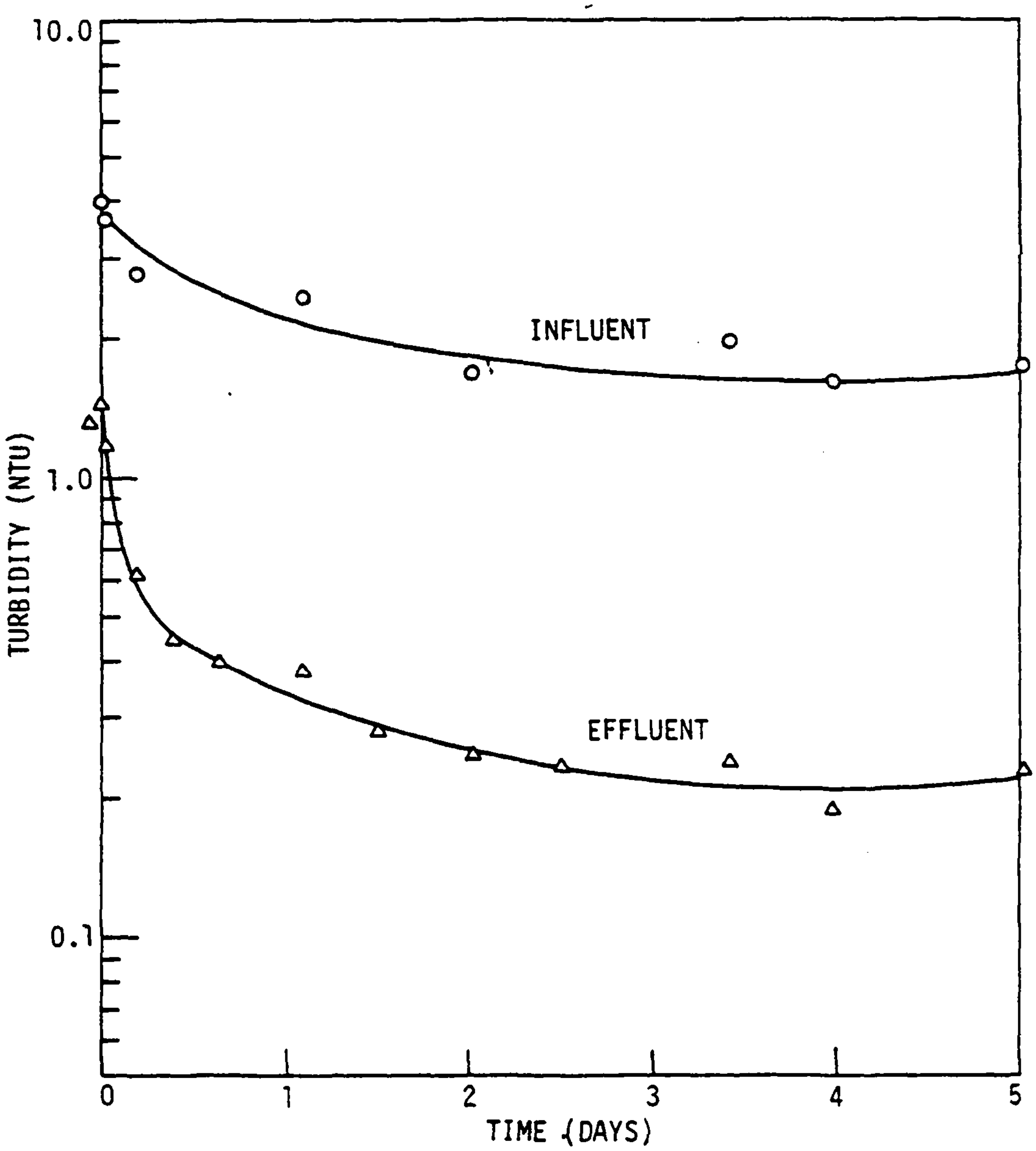

Fig. 18. Turbidity during Run B-13 at 2.9 gpm/ft^2 using Cat Floc T coagulant.

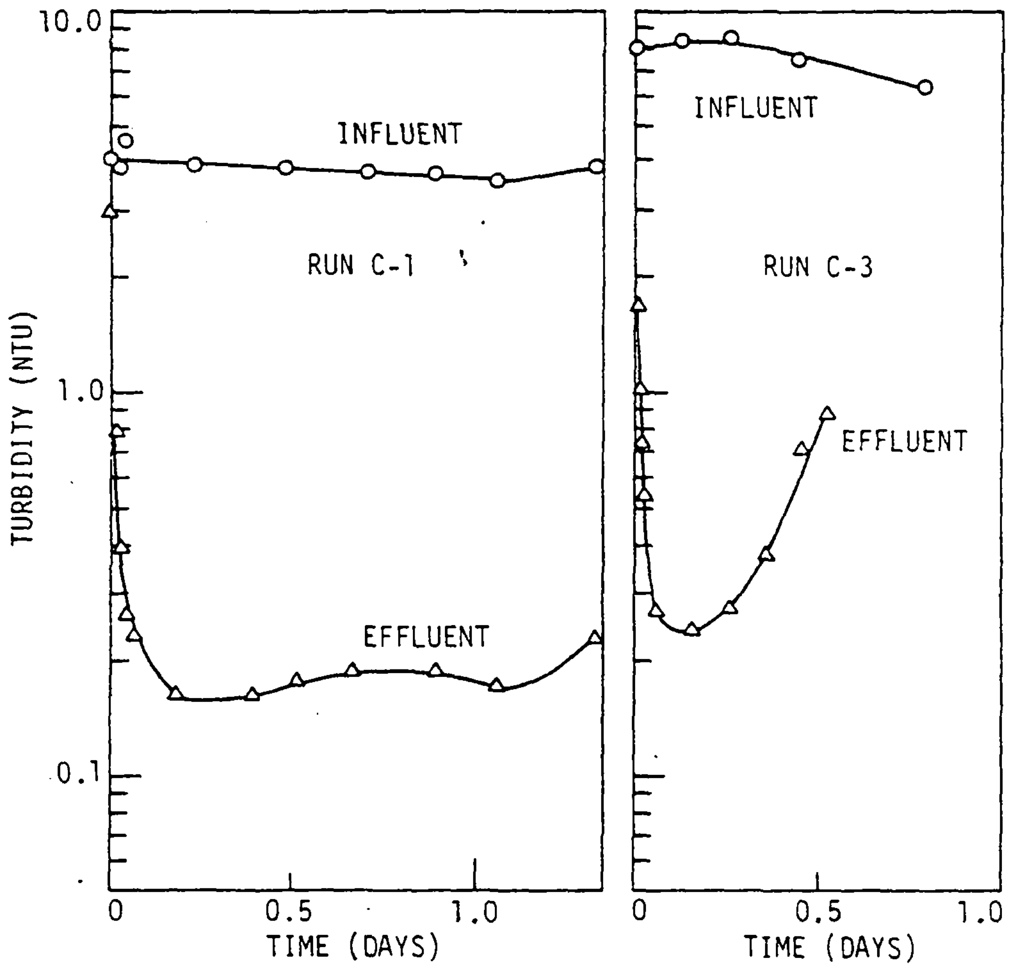

Fig. 19. Turbidity during Run C-1 and C-3 using alum coagulant. Run C-1 at 3 gpm/ft^2, Run C-3 at 4.8 gpm/ft^2.