SOME RESULTS OF EVALUATIVE TECHNIQUES APPLIED TO WASTEWATER FILTRATION

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INTRODUCTION

The current (1975) rules and regulations[1] governing deoxygenating waste effluent requirements for sewage treatment facilities in Illinois are based upon dilution ratios, i.e., the ratio of the rate of flow of the receiving stream to the rate of flow of the waste effluent. The design low flow of the stream is that flow that is likely to occur once in 10 years and persevere for a duration of 7 days. This is generally called the '7-day 10-year low flow.' For Illinois streams, these flows have been determined by Singh and Stall.[2]

As with any rule there are some exceptions. Generally, however, where the dilution ratio is less than 1:1 the BOD_5 in an effluent is not to exceed 4 mg/l and the suspended solids are not to exceed 5 mg/l. Such high quality effluent is not achievable with conventional secondary treatment. Supplemental treatment, sometimes called tertiary treatment, is required. This may take the form of settling tanks, multi-media filtration, waste stabilization ponds, settling lagoons, or micro strainers.

The basic design and construction requirements for sewage treatment works in Illinois are set forth in the *Recommended Standards for Sewage Works*,[3] prepared by the Great Lakes Upper Mississippi River Board of Sanitary Engineers. These requirements are modified from time to time by the Illinois Environmental Protection Agency (IEPA) through the issuance of technical policy releases. A WPC Technical Policy 20-24 release sets forth the basic requirements for supplemental treatment.[4] Within the framework of this technical policy, as related to multi-media filtration, at least 20 permits for the construction and operation of filtration units have been issued by IEPA.

It is not clear at this time whether the units in operation are performing up to expectations, and whether operational problems may exist even though performance from an effluent quality standpoint is satisfactory. It would be helpful, in reviewing the current design criteria, to have operational data from some of the units now in operation.

The principal purpose of the study reported here was to examine the operation of *one* installation for developing techniques that may be helpful in examining other selected installations in the state. Performance of some of the examining procedures also provided an opportunity for better understanding of the operating characteristics of multi-media filters at a sewage treatment plant.

Description of Treatment Facilities

A relatively new sewage treatment works serving the city of Washington, Illinois, was chosen for study. The facilities, designed to operate at an average dry weather flow of 0.75 million gallons per day (mgd), consists of a modified activated sludge plant (contact stabilization) followed by 4 multi-media filtration units operating in parallel. All raw sewage is pumped to the plant and flow thereafter is by gravity through the treatment units.

The 4 filtration units are identical in size and operation mode. Each filter is designed for gravity feed and is 36 inches in depth with anthracite coal atop sand, i.e., 18 inches of anthracite (0.8-1.2 mm at uniformity coefficient 1.65) and 18 inches of sand (0.5-0.6 mm at uniformity coefficient 1.6). Each unit is 11 feet in diameter providing a surface filtering area of 95 square feet. An integral part of the filter is a backwash storage tank with a volume of about 7700 gallons. The design average filtration rate is 1.40 gallons per minute per square foot (gpm/sq ft). The design average backwash rate is 15 gpm/sq ft.

Figure 1 depicts the flow regime for each of the 4 filters. As shown, sewage flow from the final clarifiers, line E, is distributed to each filter from a header box through line A during the filtering cycle. After passage through the filter, flow from the collection chamber through line B enters backwash storage and overflows a weir system through line C. During backwash, the valve on line A is closed, and that on line D is opened. The filter is backwashed to waste as the backwash tank empties. Backwash operation is preceded by a short period of air scouring. At that time the valve on line B is closed. For this study, filter 2 of the 4-battery units was chosen for examination.

Methods and Procedures

In developing methods for evaluating the filtration units we needed to obtain data regarding:

1) filter efficiency
2) filter run lengths
3) filtration rates
4) head loss development
5) backwash rates

Flow measuring devices in the plant were limited to meters recording incoming raw sewage; head loss recorders were not a part of its design features. There was, however, ready access to the header box (figure 1) which served as a sampling site for influent to the filter. Because the backwash storage tank was open to the atmosphere, the filter effluent was sampled at the weir overflow.

As part of the filtration equipment, each filter was equipped with a standpipe in which a sensing device was housed for initiating the backwash

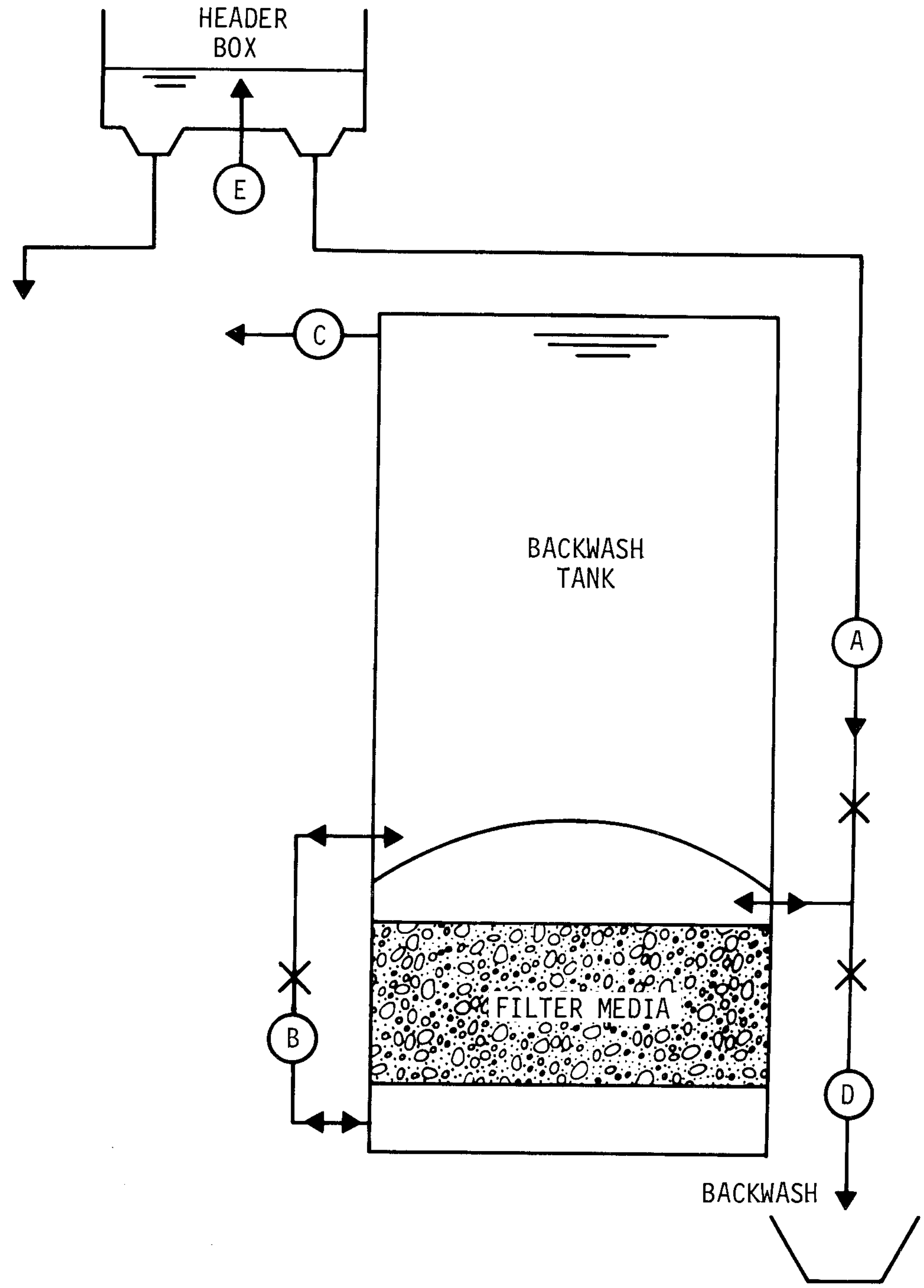


FIGURE 1

cycle. To permit a continuous record of head loss development for this study, a hole was drilled and tapped in the standpipe and a 3-inch ID plastic pipe was connected to it. The 3-inch pipe was secured to the standpipe by a split wooden platform which also served as a support for a Stevens Type F water level recorder. With a float in the 3-inch pipe actuating the recorder, a continuous record of the development of head loss on the influent side of the filter was obtained.

To gain information that would permit computation of filtration and backwash rates, another Stevens Type F water level recorder was used. It was placed atop the backwash storage tank in such a manner as to continuously register water elevations in the tank. During backwash it was an easy matter for an observer to 'mark' on the recorder chart at regular time intervals. The same procedure was used immediately after the backwash cycle to obtain the initial filtration rates. Thus the rates of tank emptying and filling were, respectively, the rates of backwash and initial filtration.

Both recorders were equipped with time scales that permitted a continuous 2-day record. In the beginning the recorders were equipped with gage scales that measured change in elevations at a ratio of 1:5. This was found to be too sensitive for the fluctuations common to the plant. A ratio of 1:10 reduced the sensitivity enough to give useful records of elevation changes. Recorder charts were changed 3 times a week thus allowing only a 1-day loss per week. This day was generally Sunday.

At the time influent and effluent sampling was performed collections were made at hourly intervals during the length of the filter run. Samples obtained during backwash were collected at 15-second intervals for the first 2 minutes of backwash and at 30-second intervals thereafter until the end of the backwash. These were analyzed in accordance with the procedures outlined in Standard Methods.[5]

Scope of Report

The data assembled during this study covered the period April 8 to May 8, 1975. All data gathered reflected the operation of filter 2. Head loss development information was obtained for 26 filter runs and the backwash sampling was accomplished on 8 occasions. Filter efficiencies, as a function of suspended solids removal, were documented on 4 separate filter runs, and the lengths of filter runs were analyzed. This report contains all the data considered useful for evaluation. Liberal use is made of figures and tables to document the operating characteristics of the multi-media filter. Conclusions are offered that may be helpful for considering the evaluations of similar filtration units.

Acknowledgments

This report was prepared under the general administrative direction of Dr. William C. Ackermann, Chief of the Illinois State Water Survey. Initial

encouragement for the study developed from conversations with Mr. Ward Akers of the Illinois Environmental Protection Agency. Without the full cooperation of Mr. Vern Attig, Superintendent of Water and Sewage, city of Washington, the study could not have been performed.

RESULTS AND DISCUSSION

The principal purpose of filtration as practiced at the city of Washington, Illinois, is to remove the residual biological floc carried over in the settled effluent from the activated sludge units. During the course of a filter run two basic cycles occur, a filtration cycle and a backwash cycle. As the filtration cycle proceeds, during which settled effluent flows through the filter media at a design rate, the head loss across the media will increase with the increasing accumulation of solids on or within the media. When a terminal head is reached, a limit set by hydraulic conditions and in this case 6 feet, filtration ceases. A filter run has been completed. The backwash cycle then commences. During the backwash cycle flow through the media is reversed and, principally through the force of hydraulic shear, residual floc is dislodged from the media and flows to waste. Following the backwash cycle the filtration cycle is ready to start. The efficiency of a filter is a function not only of suspended solids capture but also of suspended solids release.

Filter Efficiency

The influent and effluent of the filter were sampled on 4 occasions as previously described. At the end of each of the 4 filter runs samples were collected, in the manner previously outlined, from the backwash water. The characteristics of the influent and effluent of the filter for these sampling periods are shown in table 1. The average suspended solids concentration of the influent varied from about 9 to 22 mg/l. The effluent suspended solids concentration on the average varied from 1 to 2 mg/l. Chemical oxygen demand reductions were usually about 50 percent. There were not any perceptible changes in the water chemistry of the settled waste as it passed through the media.

All filters were functioning during the first 2 sampling periods (April 16 and 23). On May 6 all treated sewage flow went through only 3 filters, and on May 7 only 2 filters were taking the total sewage flow. Table 2 shows some of the features of these 4 runs.

The only questionable results shown in table 2 are those for the quantity of waste filtered. In all runs it was assumed that the total sewage flow to the plant was distributed equally to those filters in operation. This is a questionable assumption. As shown in table 2, the length of filter runs varied from 3.75 hours, when only 2 filters were operating and the average filtration rate was computed to be 5.2 gpm/sq ft, to 23.0 hours on April 23.

Table 1. Average Characteristics of Filter Influents and Effluents

	Temp. (°C)	pH	Alkal. (mg/l)	Sus. sol. (mg/l)	Vol. sol. (mg/l)	COD (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	PO_4-P (mg/l)
April 16, 1975									
Influent	9.6	7.65	258	8.7	0.4	10			
Effluent	9.6	7.65	260	1.0	0.0	5			
April 23, 1975									
Influent	11.3	7.87	218	16.0	7.0	10	0.10	7.48	0.91
Effluent	11.3	7.90	218	1.0	0.0	5	0.08	7.63	0.94
May 6, 1975									
Influent	12.8	7.68	258	22.0	6.0	24			
Effluent	12.8	7.68	258	2.0	0.0	0			
May 7, 1975									
Influent	12.2	7.60	260	21.0	9.0	20			
Effluent	12.2	7.60	260	2.0	1.0	11			

Table 2. Some Features of Four Filter Runs

	4/16/75	4/23/75	5/6/75	5/7/75
Length of run, *hr*	11.5	23.0	10.25	3.75
Length of backwash, *min*	5.0	6.5	9.0	8.5
Quantity filtered, *gal*	113,770	263,550	163,000	111,000
Average filtration rate, *gpm/sq ft*	2.0	2.0	2.8	5.2
Suspended solids load captured, *lbs*	9	33	27	18

In assessing run lengths, some consideration was given to the *Process Design Manual for Suspended Solids Removal*[6] prepared for the U. S. Environmental Protection Agency as part of its technology transfer program. This manual suggests that the lower limit for filter runs should be 6 to 8 hours to maintain reasonable net production. The upper limit should be 36 to 48 hours to avoid the creation of anaerobic conditions in the filter. From the recorded data for 26 filter runs, 11 sets of data were considered reliable enough for evaluating filter run lengths. The probability distribution of the data is shown in figure 2. The mean filter run length was 22 hours with 10 percent of the runs equal to or less than 13 hours and 90 percent equal to or less than 37 hours. Although filter runs may be limited by the deterioration of effluent quality, in the case of filter 2 at Washington all runs were limited by available head.

The suspended solids load captured by the filter during each of the 4 runs is also shown in table 2. Unfortunately, head loss development curves are not available for comparison with these differing loads which vary from 8 to 33 pounds. The influence of each filter on the operation of other filters was found to be quite pronounced and head loss curves, in many

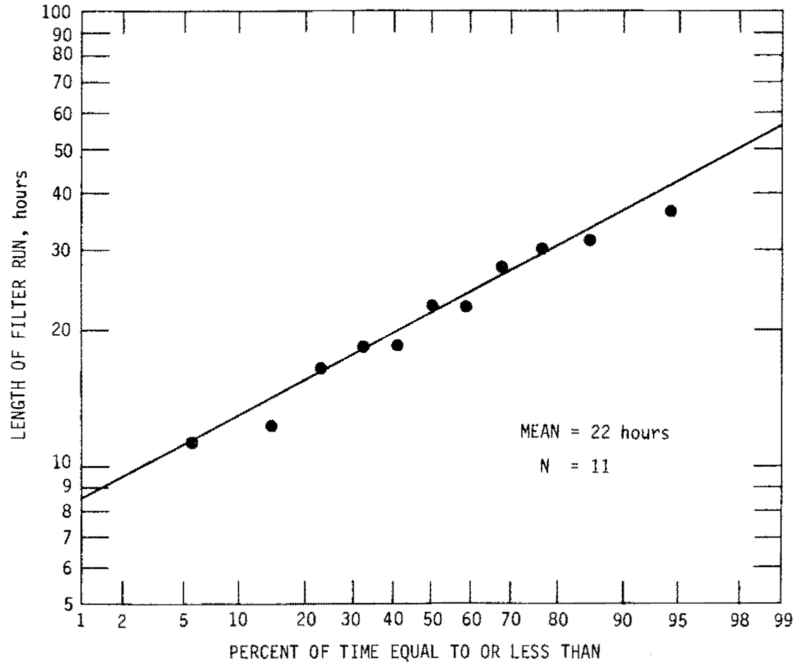


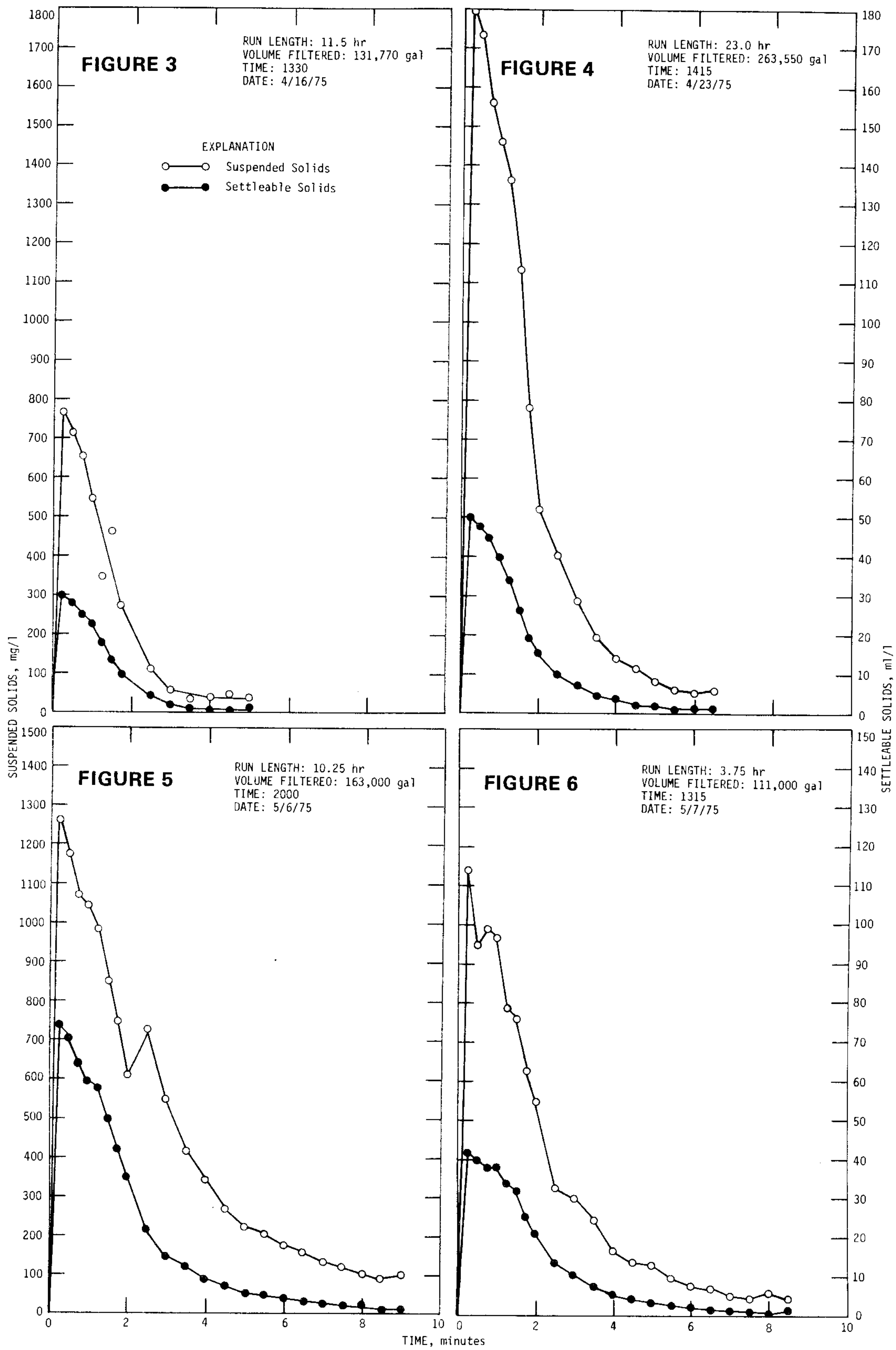
FIGURE 2

instances, were completely distorted because of these influences. This will be discussed in a later section. Nevertheless, comparison of the suspended solids load captured with the load released during backwash is interesting. The comparisons follow.

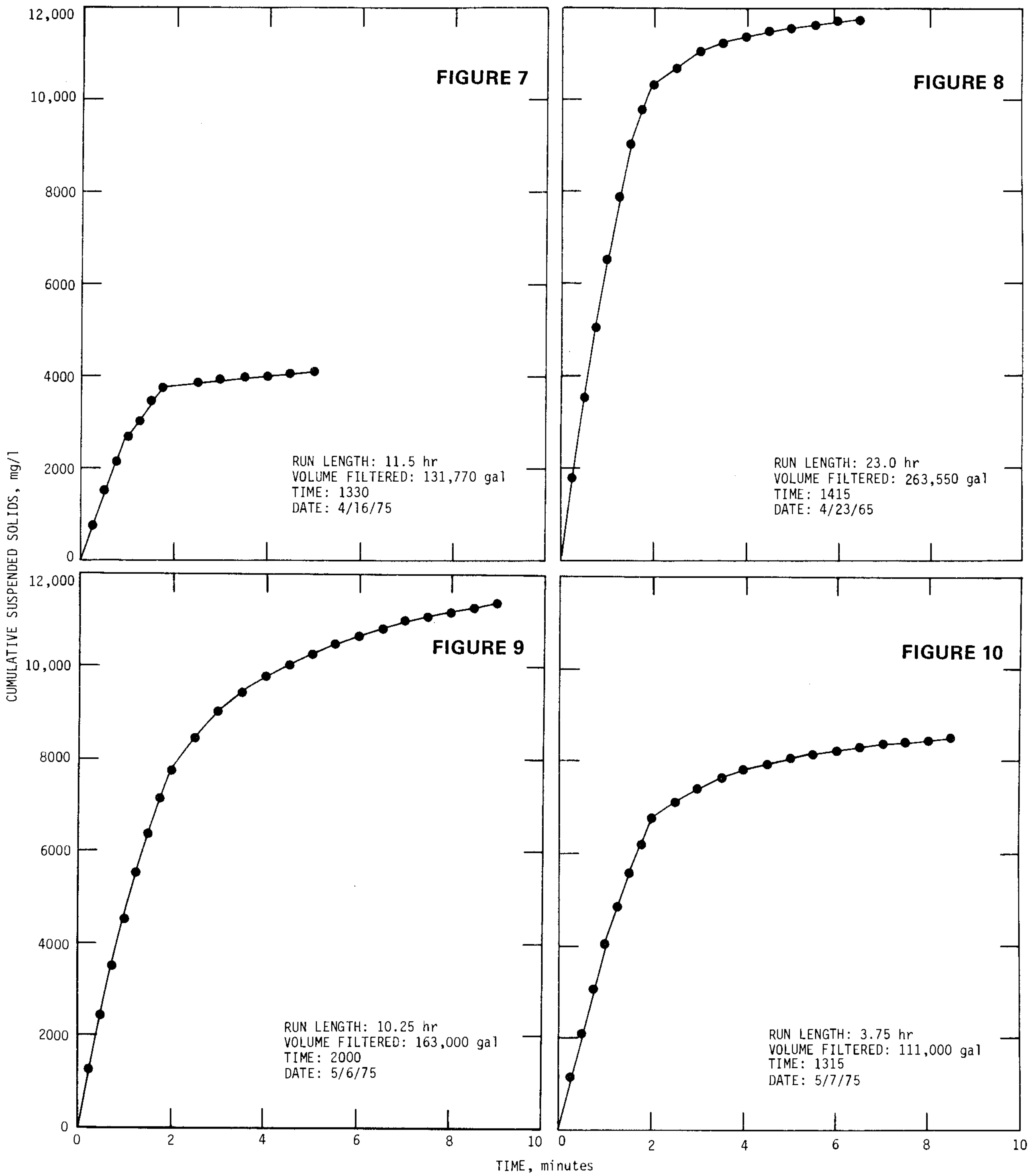
The results developed from the examination of sequential samples obtained during the backwash of filter 2 on 4 occasions are tabulated in the appendix. The patterns of suspended and settleable solids release for each of the backwashes are shown in figures 3-6. The solids release patterns are similar. Ninety percent of the solids were released within a time span of 40 to 50 percent of the total time required for backwash. As shown in table 2 the length of backwash varied from 5 to 9 minutes suggesting that some solids are retained within the filter.

The computed total suspended solids loads released during the backwashes varied from about 15 to 38 pounds. The computed equivalent depth of the solids, if equally distributed over the surface of the filter without compaction, varied from 1.2 to 2.8 inches. These data are summarized in table 3. Efforts to correlate the captured load (see table 2) with the released load were not successful. In all cases the captured load was less than the released load. It is probable that the load applied, a function of flow and influent concentration, was not too accurately determined because the assumed flow conditions were erroneous.

Cumulative suspended solids concentrations released from the backwashes are shown in figure 7-10. Here the optimal terminal time for backwashes can be estimated. The shape of the curve for the backwash cycle on May 6 (see



FIGURES 3 through 6



FIGURES 7 through 10

Table 3. Solids Load Release during Backwash

	4/16	4/23	5/6	5/7
Total suspended solids released, *lbs*	15	38	29	23
Unit suspended solids released, *lbs/sq ft*	0.16	0.40	0.30	0.24
Volume of solids released, equivalent depth, *inches*	1.2	2.0	2.8	1.8
Time to release 90% suspended solids, *minutes*	1.8	2.5	4.5	3.5

figure 9) suggests the filter was not clean at the end of backwash despite the fact that 9 minutes had elapsed during the cycle.

The data for backwash operations, set forth in the appendix, contain a tabulation for 'bulk density.' The term here means the weight of suspended solids contained in a volume of solids, i.e., the grams of solids per liter of solids (g/l). The term characterizes the 'fluffiness' of the material retained on or within the media. Generally, the bulk density varied from 25 to 40; however, on May 6 a substantial quantity of the captured material had a bulk density of 15 g/l. This is reflected in the equivalent depth of 2.8 inches noted in table 3 for that date. This suggests that the character of the suspended solids applied to the filter media will change and such changes may be detectable by the examination of the solids released from the filter. It is probable that the difficulty experienced in cleaning the filter media on May 6 (see figure 9) was caused by the 'fluffy' nature of the captured solids.

Filtration Rates

The piping arrangement for the filters at Washington is designed to permit a 'variable declining rate filtration' mode. This method differs considerably from the general practice of filtration at potable water supplies in Illinois. At public water works, rate control valves are usually an integral part of the piping scheme. These permit operation of a filtering unit at a constant rate of flow even though the head will vary. In theory the variable declining rate concept appears sound. Each filter takes that proportion of the sewage flow that the common header tanks will permit. As filtering proceeds the flow through the dirtiest filter will decrease. This causes a redistribution of the flow whereby the cleaner filters will pick up the capacity lost by the dirtier filters. In the redistribution of flow the water level rises in the header box providing the additional head required by the cleaner filters as they pick up the capacity lost by the dirtier ones.[7]

The lack of metering devices for the filtering units posed a major problem in trying to identify the filtration rates under which the filters were operating. Efforts to measure flow by recording the head on the overflow weir at the filter were not successful. The only practical means of obtaining filtration rate information was by recording the rate of fill of the backwash storage tank. These measurements provided at least some insight into the range of 'initial filtration rates.' The time of fill commences immediately after the filter has been backwashed. At this time an initial head of about 16 feet is available and this declines to about 6 feet as the tank fills. The data recorded on 7 occasions for time of fill are included in the appendix.

Figure 11 depicts the observed initial infiltration rates for filter 2 and compares the rates observed with the design average rate of 1.40 gpm/sq ft. The time to refill the tank varied from 22 to 44 minutes. A summary of the filtration rates is included in table 4.

The variation in time to fill is a function of the number of filters in operation. The fewer the number of other filters in operation the more the flow that will be tributary to the newly backwashed filters and consequently the less the time to fill. Presumably this was the basic reason for the differing rates. In every case the minimum rate observed exceeded the design average rate. This is to be expected since filtration is occurring at the time the filter is the cleanest.

On several occasions the maximum filtration rates occurred near the end of the tank filling time. This is shown in figure 11d and 11f. It is not clear why the maximum filtration rates sometimes occur when the minimum head is available.

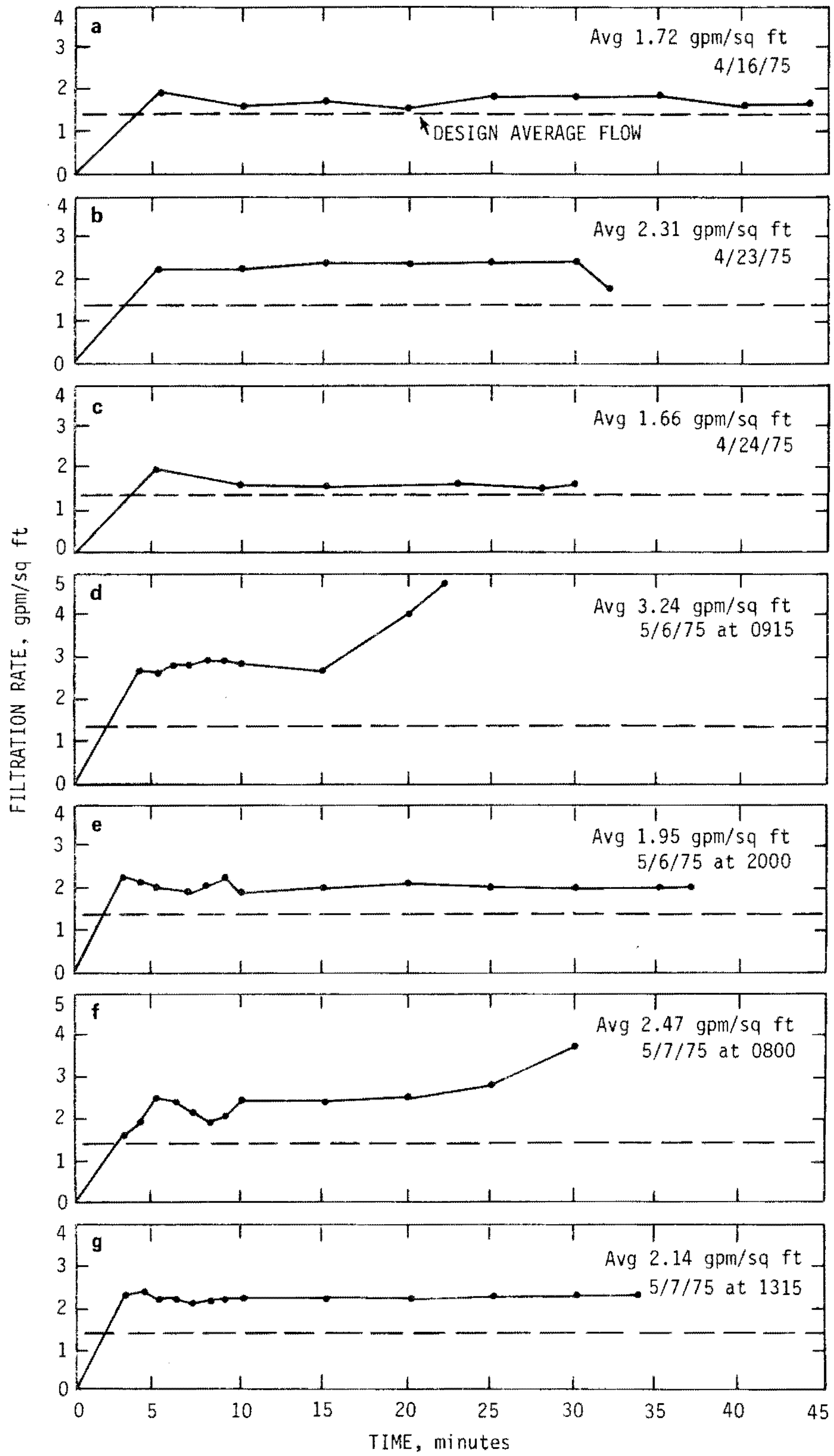
Head Loss Development

At the beginning of a filter run the only resistance encountered within the filter media is that due to the media itself. As filtration proceeds the solids captured on or within the media provide additional resistance to the filtration force. Resistance increases with increasing solids accumulation. This development of head loss was monitored on filter 2 during 26 filter runs.

The removal of suspended solids when applied to a filter may be by 1) surface straining, 2) depth filtration, and 3) a combination of surface removal and depth removal. The latter is the usual case for biological floc applied to multi-media filters.

When surface removal is the predominant mode of solids capture, head loss will be rapid, increasing at an exponential rate. For depth filtration, i.e., when the solids penetrate into the media, the head loss tends to build up linearly with time. Thus the shape of head loss development is an important characteristic in assessing the functioning of a granular media filter.

For the head loss development data gathered for 26 filter runs, a fixed reference point was not established. Rather an arbitrary datum was selected and it was assumed that each filtration cycle commenced with zero head across



FILTRATION RATE, gpm/sq ft
a
Avg 1.72 gpm/sq ft
4/16/75
DESIGN AVERAGE FLOW
b
Avg 2.31 gpm/sq ft
4/23/75
c
Avg 1.66 gpm/sq ft
4/24/75
d
Avg 3.24 gpm/sq ft
5/6/75 at 0915
e
Avg 1.95 gpm/sq ft
5/6/75 at 2000
f
Avg 2.47 gpm/sq ft
5/7/75 at 0800
g
Avg 2.14 gpm/sq ft
5/7/75 at 1315
0 5 10 15 20 25 30 35 40 45
TIME, minutes

FIGURE 11a-g

Table 4. Summary of Initial Filtration Rates

	Maximum	Average	Minimum	Time to fill
		(*gpm/sq ft*)		(*min*)
4/16/75	1.97	1.72	1.58	44
4/23/75	2.42	2.31	1.79	32
4/24/75	2.09	1.66	1.54	
5/6/75	4.75	3.24	2.62	22
5/6/75	2.31	1.95	1.80	37
5/7/75	3.72	2.47	1.56	30
5/7/75	2.38	2.14	2.09	34

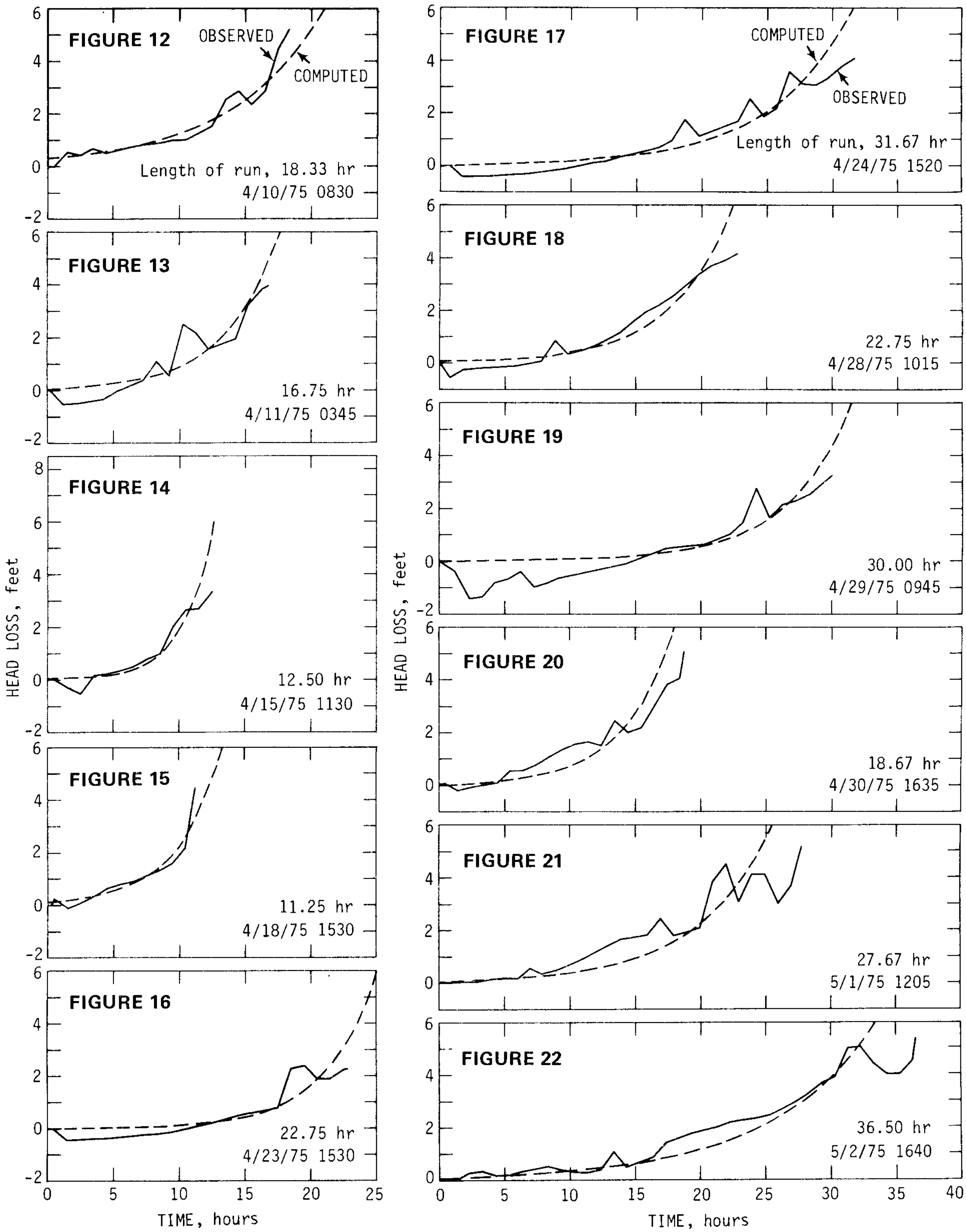
Table 5. Lines of Best Fit for Head Loss Development

Date and time	Equation	Coefficient of correlation	Figure
4/10/75 @ 0830	$y = 0.30\ e^{.142X}$	0.97	12
4/11/75 @ 0345	$y = 0.07\ e^{.253X}$	0.87	13
4/15/75 @ 1130	$y = 0.02\ e^{.450X}$	0.97	14
4/18/75 @ 1530	$y = 0.12\ e^{.298X}$	0.93	15
4/23/75 @ 1530	$y = 0.01\ e^{.256X}$	0.94	16
4/24/75 @ 1520	$y = 0.04\ e^{.160X}$	0.93	17
4/28/75 @ 1015	$y = 0.05\ e^{.218X}$	0.89	18
4/29/75 @ 0945	$y = 0.01\ e^{.205X}$	0.94	19
4/30/75 @ 1635	$y = 0.05\ e^{.268X}$	0.87	20
5/1/75 @ 1205	$y = 0.07\ e^{.179X}$	0.92	21
5/2/75 @ 1640	$y = 0.09\ e^{.124X}$	0.90	22

the filter. This was accomplished by subtracting the apparent head loss detected at the beginning of each filter run from all succeeding head loss data recorded during the run length. There is some error in this assumption but it is considered minor for comparative purposes.

The head loss data for each of the 26 filter runs were subjected to regression analyses. It was determined that data for only 11 filter runs were sufficiently correlated in terms of head loss versus time to mainly reflect the accumulation of suspended solids. The rejected data consisted of 3 abbreviated records and other head loss data that were significantly influenced by plant operations other than that of suspended solids capture. A plot of the observations for 11 data sets are shown in figures 12-22. Also included on the figures is a line of best fit determined from the exponential relationship:

$$y = a\ e^{bx}$$



FIGURES 12 through 22

where

y = head loss in feet

x = time in hours

a and b = coefficients

The equations developed and corresponding coefficients of correlation are summarized in table 5.

The irregularities of the head loss developments shown in figures 12-22 are the influence of other filters in the system. For example, figure 17 indicates that 3 backwashing operations occurred at other units producing periodic, but temporary, excessive head loss conditions on filter 2. The computed line of best fit tends to idealize the head loss development. It is apparent, however, when comparing these figures that major differences exist in shape and duration of head loss development.

For example figures 12 through 15 and figure 20 represent shortened filtration run lengths.

The shape of the curves, being rather pronounced exponentially, suggests that the principal method of suspended solids capture was by surface straining. On the other hand the data in figures 16-19 and 21 and 22 represent longer runs, and the earlier hours of head loss development appear linear but terminate in an exponential fashion. Here a combination of depth filtration followed by surface straining appears to be the manner of suspended solids removal.

Observations of head loss development for the 26 filter runs are included in the appendix.

Backwash Rates

It has been stated that the backwashing technology gained from water treatment practice cannot be readily transferred to wastewater treatment practice.[7] This is mainly because wastewater units receive heavier solids loads which adhere more tenaceously to the media. Backwashing is usually preceded by air scour or surface wash. In the plant at Washington air scour is used.

Backwash rates for filter 2 were determined by the rate the backwash storage tank emptied. Eight occurrences were recorded and the observed data are included in the appendix. The backwash water is furnished to the filter media at a falling head. This arrangement produces substantial backwash rates at the beginning of the cycle with the rates then dropping precipitously. This is shown in figure 23. In spite of the design rate of 15 gpm/sq ft the backwash rate generally only equals or exceeds that rate during the first 15 seconds of the cycle. A summary of backwash rates is given in table 6.

The time for the backwash cycle varied from 5.5 to 9.0 minutes. During the earlier backwash cycles the average rates were about 67 percent of the design rate. Later backwashing occurrences revealed an average backwash rate

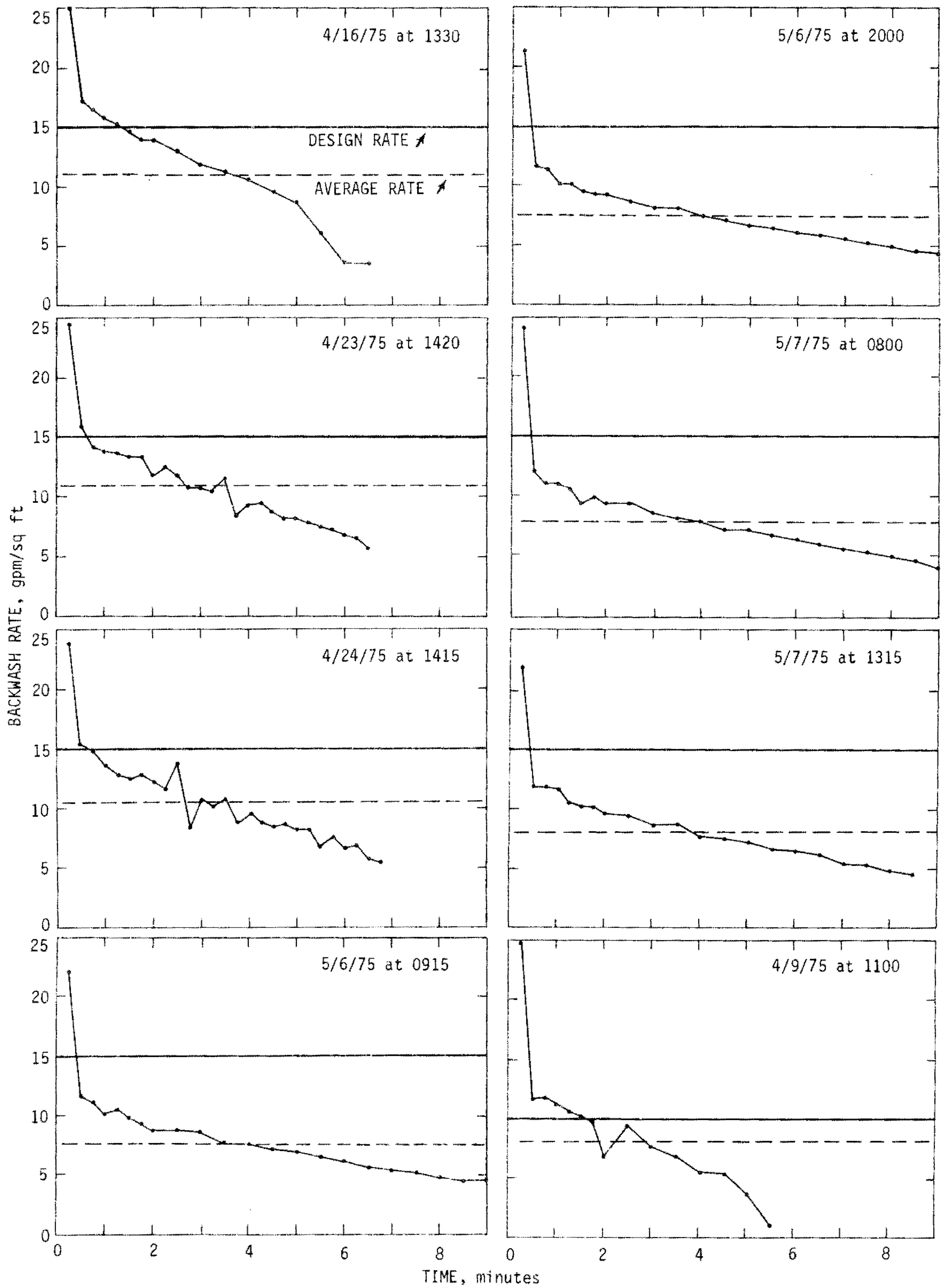

4/16/75 at 1330
DESIGN RATE
AVERAGE RATE
5/6/75 at 2000
4/23/75 at 1420
5/7/75 at 0800
4/24/75 at 1415
5/7/75 at 1315
5/6/75 at 0915
4/9/75 at 1100
BACKWASH RATE, gpm/sq ft
TIME, minutes
0
5
10
15
20
25
0
2
4
6
8

FIGURE 23

Table 6. Summary of Backwash Rates

	Maximum	Average (*gpm/sq ft*)	Minimum	Time required (*min*)
4/9/75	29.9	13.0	6.0	5.5
4/16/75	25.1	11.2	3.6	6.5
4/23/75	24.5	10.9	5.7	6.5
4/24/75	23.9	10.5	5.4	6.8
5/6/75	22.1	7.6	4.6	9.0
5/6/75	21.3	7.5	4.3	9.0
5/7/75	23.9	7.8	4.5	9.0
5/7/75	21.9	8.1	4.6	8.5

of about 50 percent of the design rate. The reasons for this are not clear, and because the filter is completely enclosed no visual assessment of the filter media is possible. It is conceivable that some air binding may be occurring or some clogging of the drains to waste may be involved.

Microscopic examinations were made of the solids released from the filter. Much of the organic matter consisted of protozoa common to the activated sludge process as well as diatoms, nematodes, blue-green algae, actinomycetes, and rotifers. These organisms are capable of causing flow restrictions within conduits.

CONCLUSIONS

The principal intent of the study, as mentioned earlier, was to determine what techniques might be useful for assessing the performance of on-line tertiary filter units. Obviously each installation will provide a different challenge to the development of information. However, the basic concept of establishing procedures for evaluating 1) filter efficiency, 2) filtration rates, 3) head loss development, and 4) backwash rates at any installation appears sound. This is a well balanced approach because each operation is intimately related to the other. The inability here to compare solids capture with solids release emphasizes the necessity for reliable flow data for the unit being assessed. Also it seems important to develop corresponding influent loads, filtration and backwash rates, as well as head loss curves. For the collection of the data assembled during this study about 36 man-days were required. About one-third of the time was required in the field and two-thirds in the laboratory. Approximately equal time was required for evaluating the data and developing the first draft of a report.

Although it is rather risky to offer suggestions regarding design criteria based upon the observations of only one plant, certain tentative thoughts are nevertheless offered. These include:

1) For proper operating control the sewage flow to each filter should be metered and head loss recorded.
2) Specification for backwash rates should not rely on *average* rates but, on the contrary, should provide for a reasonably constant rate with deviations of ± 2 gpm/sq ft.
3) Where possible, all filter units should be open to the atmosphere.
4) Influent, effluent, and backwash conduits should be available for sampling and should be situated to permit visual inspection.
5) Engineering justification should be submitted warranting the omission of positive flow-rate control devices for the filters.

It is important to realize that most of the data presented in this report are not available to the manager of the Washington plant during routine operation of that plant. It should be.

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Appendix 1. Characteristics of Filter Backwash Water

Time (*min*)	pH	Alkal. (*mg/l*)	Sus. sol. (*mg/l*)	Vol. sol. (*mg/l*)	COD (*mg/l*)	Set. sol. (*ml/l*)	Bulk den. (*g/l*)
April 16, 1975							
0.25	7.88	271	764	254	524	30	25
0.50	7.88	271	714	238	496	28	25
0.75	7.80	269	652	212	495	25	25
1.00	7.80	269	548	180	498	23	23
1.25	7.70	266	348	112	262	18	18
1.50	7.74	269	464	84	183	14	34
1.75	7.73	264	274	90	163	10	27
2.00	(*container broke*)						
2.50	7.67	259	111	35	100	5	24
3.00	7.68	260	61	16	24	2	30
3.50	7.63	260	35	9	21	3	21
4.00	7.66	260	41	12	22	1	49
4.50	7.60	258	52	16	21	1	50
5.00	7.60	258	39	12	19	1	29
April 23, 1975							
0.25	7.80	240	1794	848	876	50	35
0.50	7.80	240	1738	818	791	48	35
0.75	7.80	238	1562	752	756	45	34
1.00	7.80	235	1462	688	724	40	35
1.25	7.80	231	1362	648	439	34	39
1.50	7.80	230	1134	528	336	26	40
1.75	7.80	226	782	354	269	20	38
2.00	7.80	222	522	238	220	16	32
2.50	7.80	218	403	188	196	10	37
3.00	7.82	218	288	121	149	7	38
3.50	7.78	217	195	91	77	5	35
4.00	7.78	218	141	65	58	4	36
4.50	7.78	217	119	51	46	3	42
5.00	7.78	216	84	39	45	2	36
5.50	7.78	216	63	26	33	1	39
6.00	7.80	216	56	25	27	1	39
6.50	7.78	218	61	24	24	1	47
May 6, 1975							
0.25	7.67	343	1264	404	1308	74	15
0.50	7.60	341	1176	388	1242	71	15
0.75	7.60	336	1072	332	1109	65	15
1.00	7.60	336	1044	340	769	60	16
1.25	7.60	331	984	288	726	58	15
1.50	7.62	328	852	264	696	50	15
1.75	7.60	311	748	208	677	43	15
2.00	7.60	304	612	172	546	35	15
2.50	7.60	291	730	232	436	22	30
3.00	7.60	289	550	164	354	15	33
3.50	7.60	279	418	130	239	13	31

(Continued on the next page)

Appendix 1. Concluded

Time (*min*)	pH	Alkal. (*mg/l*)	Sus. sol. (*mg/l*)	Vol. sol. (*mg/l*)	COD (*mg/l*)	Set. sol. (*ml/l*)	Bulk den. (*g/l*)
May 6, 1975 (continued)							
4.00	7.60	275	344	104	136	9	34
4.50	7.60	271	270	46	116	8	33
5.00	7.60	266	228	50	100	6	37
5.50	7.60	266	208	52	89	5	36
6.00	7.60	266	178	52	75	4	36
6.50	7.60	263	161	44	70	4	39
7.00	7.60	263	137	39	73	3	36
7.50	7.60	261	125	37	65	3	39
8.00	7.60	260	107	29	62	2	34
8.50	7.60	258	96	26	45	1	53
9.00	7.60	258	102	28	49	1	57
May 7, 1975							
0.25	7.63	328	1140	464	595	42	24
0.50	7.63	317	948	372	641	40	21
0.75	7.63	316	996	220	643	38	24
1.00	7.63	306	967	367	683	38	23
1.25	7.63	304	793	313	655	34	21
1.50	7.63	300	760	280	653	32	21
1.75	7.63	297	627	220	442	26	22
2.00	7.63	289	547	194	475	21	23
2.50	7.63	285	327	107	295	14	21
3.00	7.63	283	300	107	285	11	26
3.50	7.63	271	244	92	138	8	28
4.00	7.63	270	168	52	151	6	28
4.50	7.63	269	136	48	98	5	26
5.00	7.63	265	130	42	84	4	33
5.50	7.63	264	97	35	75	3	26
6.00	7.63	260	79	17	43	2	34
6.50	7.63	260	70	27	38	2	34
7.00	7.63	260	50	17	34	2	28
7.50	7.63	260	45	34	30	1	29
8.00	7.63	258	58	44	30	1	46
8.50	7.63	258	43	32	27	1	26

Appendix 2. Filling of Backwash Storage Tank (Initial Filtering)

4/16/75		4/23/75		4/24/75		5/6/75		5/6/75		5/7/75		5/7/75	
Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)
0	10.05	0	9.92	0	9.80	0	9.71	0	9.72	0	9.86	0	9.82
5	8.73	5	8.39	5	8.40	4	8.29	2	9.58	2	9.77	1	9.75
10	7.63	10	6.87	10	7.34	5	7.94	3	9.27	3	9.56	2	9.68
15	6.48	15	5.29	15	6.27	6	7.57	4	8.97	4	9.30	3	9.37
20	5.45	20	3.71	23	4.59	7	7.19	5	8.70	5	8.96	4	9.05
25	4.27	25	2.12	28	3.56	8	6.80	6	8.46	6	8.64	5	8.76
30	3.09	30	0.50	30	3.14	9	6.40	7	8.20	7	8.35	6	8.47
35	1.92	35	0.02	(Incomplete)		10	6.03	8	7.92	8	8.10	7	8.19
40	0.86					15	4.20	9	7.62	9	7.83	8	7.90
44	0.03					20	1.52	10	7.36	10	7.51	9	7.60
						22	0.04	15	6.00	15	5.88	10	7.30
								20	4.58	20	4.23	15	5.84
								25	3.21	25	2.37	20	4.37
								30	1.90	30	0.13	25	2.83
								35	0.61			30	1.32
								37	0.07			34	0.15

Appendix 3. Observations of Head Loss Development

Date→	4/10/75		4/11/75		4/11/75		4/14/75	
Start of run→	0830		0345		2115		1330	
	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)
	0.00	0	0.0	0	0.0	0	0.00	0
	0.00	0.5	0.0	0.25	0.08	0.75	0.00	0.25
	0.52	1.5	-0.54	1.25	-0.32	1.75	0.02	0.50
	0.14	2.5	-0.50	2.25	-0.18	2.75	0.42	1.50
	0.68	3.5	-0.41	3.25	-0.03	3.75	-0.22	2.50
	0.51	4.5	-0.35	4.25	0.15	4.75	-0.08	3.50
	0.61	5.5	-0.06	5.25	0.57	5.75	0.00	4.50
	0.75	6.5	0.14	6.25	0.29	6.75	0.17	5.50
	0.82	7.5	0.36	7.25	0.32	7.75	0.39	6.50
	0.87	8.5	1.09	8.25	0.42	8.75	0.48	7.50
	0.99	9.5	0.50	9.25	0.51	9.75	0.64	8.50
	1.01	10.5	2.50	10.25	0.59	10.75	0.71	9.50
	1.25	11.5	2.17	11.25	0.82	11.75	5.38	10.50
	1.57	12.5	1.52	12.25	1.18	12.75	5.38	11.50
	2.55	13.5	1.77	13.25				
	2.86	14.5	1.94	14.25				
	2.37	15.5	3.22	15.25				
	2.87	16.5	3.80	16.25				
	4.46	17.5	3.94	16.75				
	5.20	18.33						

Date→	4/15/75		4/16/75		4/16/75		4/17/75	
Start of run→	1130		0120		1430		1030	
	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)
	0.00	0	0.00	0	0.00	0	0.00	0
	0.00	0.17	0.00	0.17	0.00	0.25	0.06	0.17
	0.01	0.50	-0.12	0.67	0.05	0.50	-0.42	0.50
	-0.30	1.50	-0.65	1.67	0.09	1.50	0.24	1.50
	-0.52	2.50	-0.72	2.67	0.08	2.50	0.59	2.50
	0.16	3.50	-0.82	3.67	-0.92	3.50	0.89	3.50
	0.22	4.50	-0.70	4.67	0.12	4.50	0.44	4.50
	0.33	5.50	-0.52	5.67	0.24	5.50	0.64	5.50
	0.48	6.50	-0.15	6.67	0.97	6.50	0.07	6.50
	0.73	7.50	0.65	7.67	1.04	7.50	0.29	7.50
	0.97	8.50	1.24	8.67	0.63	8.50	0.51	8.50
	2.00	9.50	0.80	9.67	0.65	9.50	5.14	9.50
	2.65	10.50	0.88	10.67	0.67	10.50		10.50
	2.70	11.50	0.90	11.67	0.61	11.50		
	3.30	12.50			0.57	12.50		
					0.45	13.50		
					0.52	14.50		
					0.61	15.50		
					0.61	16.50		
					0.93	17.50		
					3.64	18.50		
					4.10	18.83		

*HL = Head Loss

(Continued on the next page)

Appendix 3. Continued

Date→	4/18/75		4/19/75		4/21/75		4/22/75	
Start of run→	1530		1310		0830		1015	
	HL* (*ft*)	Time (*hrs*)	HL* (*ft*)	Time (*hrs*)	HL* (*ft*)	Time (*hrs*)	HL* (*ft*)	Time (*hrs*)
	0.00	0	0.00	0	0.00	0	0.00	0
	0.00	0.33	0.00	0.17	-0.81	0.50	2.15	0.75
	0.22	0.50	0.04	0.83	0.00	1.50	6.75	1.75
	-0.12	1.50	0.09	1.83	0.05	2.50	7.35	2.75
	0.09	2.50	0.13	2.83	0.27	3.50	3.95	3.75
	0.32	3.50	0.17	3.83	0.37	4.50	4.55	4.75
	0.61	4.50	0.45	4.83	1.28	5.50	4.82	5.57
	0.78	5.50	0.33	5.83	1.90	6.50	4.94	6.75
	0.88	6.50	0.49	6.83	2.27	7.50	4.43	7.75
	1.12	7.50	0.61	7.83	3.68	8.50	4.69	8.75
	1.30	8.50	0.70	8.83	5.80	9.50	4.80	9.75
	1.58	9.50	0.79	9.83	5.80	14.83	5.12	10.75
	2.19	10.50	0.90	10.83			5.21	11.75
	4.44	11.25	1.02	11.83			5.44	12.75
			1.13	12.83			5.53	13.75
			1.22	13.83			5.82	14.75
			1.38	14.83			6.23	15.75
			1.50	15.83			6.58	16.75
			1.67	16.83			6.87	17.75
			1.88	17.83			7.20	18.75
			2.03	18.83			7.58	19.75
			2.23	19.83				

*HL = Head Loss

(Continued on the next page)

Appendix 3. Continued

Date→	4/23/75		4/23/75		4/24/75		4/25/75
Start of run→	0815		1530		1520		2345
HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)
0.00	0	0.00	0	0.00	0	0.00	0
0.56	0.75	0.00	0.50	0.00	0.67	0.00	0.25
0.59	1.75	-0.43	1.50	-0.46	1.67	0.05	1.25
0.17	2.75	-0.42	2.50	-0.43	2.67	0.15	2.25
0.28	3.75	-0.39	3.50	-0.43	3.67	0.28	3.25
0.39	4.75	-0.38	4.50	-0.38	4.67	0.43	4.25
1.18	5.75	-0.32	5.50	-0.33	5.67	0.62	5.25
0.50	6.08	-0.27	6.50	-0.31	6.67	1.50	6.25
		-0.22	7.50	-0.25	7.67	1.16	7.25
		-0.19	8.50	-0.20	8.67	1.49	8.25
		-0.12	9.50	-0.13	9.67	1.78	9.25
		-0.02	10.50	-0.02	10.67	1.97	10.25
		0.11	11.50	0.09	11.67	2.19	11.25
		0.20	12.50	0.16	12.67	3.27	12.25
		0.33	13.50	0.31	13.67	2.78	13.25
		0.48	14.50	0.42	14.67	3.10	14.25
		0.58	15.50	0.55	15.67	3.46	15.25
		0.68	16.50	0.69	16.67	3.55	15.75
		0.77	17.50	0.94	17.67		
		2.27	18.50	1.74	18.67		
		2.37	19.50	1.11	19.67		
		1.88	20.50	1.31	20.67		
		1.88	21.50	1.48	21.67		
		2.21	22.50	1.66	22.67		
		2.26	22.75	2.52	23.67		
				1.84	24.67		
				2.20	25.67		
				3.56	26.67		
				3.10	27.67		
				3.06	28.67		
				3.31	29.67		
				3.74	30.67		
				4.07	31.67		

*HL = Head Loss

(Continued on the next page)

Date→	4/28/75		4/29/75		4/30/75		5/1/75	
Start of run→	1015		0945		1635		1205	
	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)	HL* (ft)	Time (hrs)
	0.00	0	0.00	0	0.00	0	0.00	0
	0.00	0.08	0.00	0.25	0.00	0.08	0.00	0.17
	-0.58	0.75	-0.39	1.25	0.04	0.42	0.03	0.92
	-0.27	1.75	-1.41	2.25	-0.19	1.42	0.02	1.92
	-0.21	2.75	-1.33	3.25	-0.10	2.42	0.04	2.92
	-0.17	3.75	-0.81	4.25	0.01	3.42	0.13	3.92
	-0.13	4.75	-0.69	5.25	0.09	4.42	0.19	4.92
	-0.11	5.75	-0.41	6.25	0.55	5.42	0.13	5.92
	-0.03	6.75	-0.98	7.25	0.54	6.42	0.54	6.92
	0.05	7.75	-0.84	8.25	0.78	7.42	0.35	7.92
	0.84	8.75	-0.68	9.25	1.05	8.42	0.49	8.92
	0.36	9.75	-0.56	10.25	1.34	9.42	0.66	9.92
	0.48	10.75	-0.43	11.25	1.53	10.42	0.89	10.92
	0.63	11.75	-0.32	12.25	1.64	11.42	1.17	11.92
	0.88	12.75	-0.24	13.25	1.51	12.42	1.42	12.92
	1.14	13.75	-0.12	14.25	2.43	13.42	1.69	13.92
	1.58	14.75	0.08	15.25	2.00	14.42	1.73	14.92
	1.92	15.75	0.26	16.25	2.19	15.42	1.81	15.92
	2.19	16.75	0.45	17.25	3.02	16.42	2.44	16.92
	2.51	17.75	0.51	18.25	3.82	17.42	1.80	17.92
	2.94	18.75	0.56	19.25	4.04	18.42	1.90	18.92
	3.35	19.75	0.58	20.25	5.04	18.67	2.05	19.92
	3.70	20.75	--	21.25			3.86	20.92
	3.88	21.75	1.01	22.25			4.52	21.92
	4.12	22.75	1.48	23.25			3.07	22.92
			2.76	24.25			4.14	23.92
			1.63	25.25			4.12	24.92
			2.15	26.25			3.01	25.92
			2.28	27.25			3.69	26.92
			2.52	28.25			5.18	27.67
			2.92	29.25				
			3.27	30.00				

*HL = Head Loss

(Continued on the next page)

Appendix 3. Continued

Date→	5/2/75		5/5/75		5/6/75		5/6/75	
Start of run→	1640		1100		0940		2045	
	HL* *(ft)*	Time *(hrs)*	HL* *(ft)*	Time *(hrs)*	HL* *(ft)*	Time *(hrs)*	HL* *(ft)*	Time *(hrs)*
	0.00	0	0.00	0	0.00	0	0.00	0
	0.00	0.01	-0.36	1.00	0.00	0.08	0.00	0.25
	0.01	0.33	-0.34	2.00	-1.94	0.33	0.21	1.25
	0.01	1.33	0.34	3.00	-2.14	1.33	2.79	2.25
	0.29	2.33	0.17	4.00	-0.96	2.33	0.26	3.25
	0.34	3.33	-0.33	5.00	-2.44	3.33	0.24	4.25
	0.16	4.33	-0.26	6.00	-0.80	4.33	0.07	5.25
	0.20	5.33	0.26	7.00	1.28	5.33	1.21	6.25
	0.30	6.33	0.30	8.00	0.81	6.33	-0.22	7.25
	0.40	7.33	0.53	9.00	-0.56	7.33	0.05	8.25
	0.51	8.33	1.66	10.00	-0.44	8.33	-0.09	9.25
	0.38	9.33	0.96	11.00	1.66	9.33	--	10.25
	0.28	10.33	1.22	12.00	0.55	10.08	0.74	11.25
	0.26	11.33	2.46	13.00	Filters		1.58	12.00
	0.38	12.33	1.74	14.00	2, 3, & 4		Filters	
	1.03	13.33	1.02	15.00			2, 3, & 4	
	0.45	14.33	0.63	16.00				
	0.62	15.33	0.65	17.00				
	0.82	16.33	0.56	18.00				
	1.39	17.33	0.71	19.00				
	1.54	18.33	1.36	20.00				
	1.74	19.33	4.38	21.00				
	1.86	20.33		22.00				
	1.97	21.33						
	2.18	22.33						
	2.23	23.33						
	2.31	24.33						
	2.43	25.33						
	2.67	26.33						
	2.94	27.33						
	3.23	28.33						
	3.64	29.33						
	3.88	30.33						
	4.96	31.33						
	5.02	32.33						
	4.38	33.33						
	3.97	34.33						
	4.00	35.33						
	4.46	36.33						
	5.36	36.50						

*HL = Head Loss

(Continued on the next page)

Appendix 3. Concluded

Date→	5/7/75		5/7/75	
Start of run→	0915		1345	
	HL* (*ft*)	Time (*hrs*)	HL* (*ft*)	Time (*hrs*)
	0.00	0	0.00	0
	0.00	0.75	0.00	0.25
	0.47	1.75	0.16	1.25
	1.13	2.75	0.31	2.25
	2.28	3.75	1.02	3.25
	Filters		0.85	4.25
	2 & 3		0.93	5.25
			0.39	6.25
			0.43	7.25
			1.22	8.25
			0.93	9.25
			1.06	10.25
			0.90	11.25
			1.68	12.25
			0.52	13.25
			0.90	14.25
			3.46	15.25
			4.02	16.25
			4.53	16.75

*HL = Head Loss

Appendix 4. Emptying of Backwash Tank

Date→	4/9/75		4/16/75		4/23/75		4/24/75	
Start of backwash→	1100		1330		1420		1415	
	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)
	0.00	0	0.08	0	0.10	0	0.12	0
	1.00	0.25	0.92	0.25	0.92	0.25	0.92	0.25
	1.56	0.50	1.50	0.50	1.45	0.50	1.43	0.50
	2.12	0.75	2.05	0.75	1.94	0.75	1.93	0.75
	2.66	1.00	2.58	1.00	2.40	1.00	2.39	1.00
	3.18	1.25	3.09	1.25	2.86	1.25	2.82	1.25
	3.69	1.50	3.58	1.50	3.30	1.50	3.24	1.50
	4.19	1.75	4.05	1.75	3.74	1.75	3.67	1.75
	4.59	2.00	4.52	2.00	4.14	2.00	4.08	2.00
	5.55	2.50	5.39	2.50	4.56	2.25	4.47	2.25
	6.39	3.00	6.19	3.00	4.96	2.50	4.93	2.50
	7.18	3.50	6.94	3.50	5.32	2.75	5.21	2.75
	7.88	4.00	7.65	4.00	5.68	3.00	5.57	3.00
	8.57	4.50	8.29	4.50	6.03	3.25	5.91	3.25
	9.15	5.00	8.87	5.00	6.42	3.50	6.27	3.50
	9.55	5.50	9.28	5.50	6.70	3.75	6.57	3.75
			9.53	6.00	7.01	4.00	6.89	4.00
			9.77	6.50	7.33	4.25	7.19	4.25
					7.63	4.50	7.47	4.50
					7.90	4.75	7.76	4.75
					8.17	5.00	8.03	5.00
					8.43	5.25	8.30	5.25
					8.68	5.50	8.53	5.50
					8.92	5.75	8.78	5.75
					9.15	6.00	9.00	6.00
					9.37	6.25	9.23	6.25
					9.56	6.50	9.43	6.50
							9.61	6.75

(Continued on the next page)

Appendix 4. Concluded

Date→	5/6/75		5/6/75		5/7/75		5/7/75	
Start of backwash→	0915		2000		0800		1315	
	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)	Elev (*ft*)	Time (*min*)
	0.14	0	0.10	0	0.11	0	0.20	0
	0.88	0.25	0.81	0.25	0.91	0.25	0.93	0.25
	1.27	0.50	1.20	0.50	1.31	0.50	1.33	0.50
	1.64	0.75	1.58	0.75	1.68	0.75	1.73	0.75
	1.98	1.00	1.92	1.00	2.05	1.00	2.12	1.00
	2.33	1.25	2.26	1.25	2.40	1.25	2.47	1.25
	2.66	1.50	2.58	1.50	2.71	1.50	2.81	1.50
	2.97	1.75	2.89	1.75	3.04	1.75	3.15	1.75
	3.27	2.00	3.20	2.00	3.35	2.00	3.47	2.00
	3.87	2.50	3.78	2.50	3.97	2.50	4.10	2.50
	4.45	3.00	4.33	3.00	4.54	3.00	4.68	3.00
	4.97	3.50	4.87	3.50	5.08	3.50	5.27	3.50
	5.47	4.00	5.37	4.00	5.60	4.00	5.78	4.00
	5.95	4.50	5.84	4.50	6.08	4.50	6.29	4.50
	6.42	5.00	6.29	5.00	6.56	5.00	6.77	5.00
	6.86	5.50	6.72	5.50	7.01	5.50	7.22	5.50
	7.27	6.00	7.13	6.00	7.43	6.00	7.66	6.00
	7.66	6.50	7.52	6.50	7.83	6.50	8.07	6.50
	8.02	7.00	7.89	7.00	8.20	7.00	8.43	7.00
	8.37	7.50	8.24	7.50	8.55	7.55	8.79	7.50
	8.70	8.00	8.57	8.00	8.87	8.00	9.12	8.00
	9.01	8.50	8.88	8.50	9.18	8.50	9.43	8.50
	9.32	9.00	9.17	9.00	9.48	9.00		