SOME EFFECTS OF ORGANIC AND HYDRAULIC LOADINGS ON A FIXED-BED REACTOR

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CHAPTER I

INTRODUCTION

General

The term "trickling filter" is misleading in that it connotes a physical process of filtration, as of a liquid through a fine, porous paper. Actually, the trickling filter would be more properly termed a fixed bed reactor, or, more exactly:

> An artificial bed of coarse material such as broken stone, clinkers, slate, slats, or brush, over which sewage is distributed and applied in drops, films, or spray, from troughs or drippers, moving distributors, or fixed nozzles, and through which it trickles to the underdrains giving opportunity for organic matter to be oxidized by biochemical agencies (15).

The trickling filter process, first used about 1908, is one of the oldest and yet one of the least understood methods of treating waste and waste products. In the sixty years since the inception of the trickling filter, many noted authorities have performed painstaking research on the variables of the system and the kinetics of the process, and yet hardly any two of them agree as to their findings. It appears that the process variables are so many and so interrelated that there are any number of possible relationships between the variables that affect the performance of the filter. Some of these process variables are:

1. Organic Loading
2. Hydraulic Loading
3. pH

4. Temperature
5. Method and Rate of Waste Application
6. Depth of Filter
7. Contact Time in the Filter
8. Recirculation
9. Active Film Surface Area

Justification of This Research

Because of the wide disagreement among the authorities in the field of waste treatment about the interaction of these process variables, it is felt that additional research into the nature of the trickling filter process is justified. This research will serve to help clarify certain of the areas in which there is the most disagreement, notably in the areas of organic loading and hydraulic loading interaction.

Another aspect was to investigate the change in pH of the filter liquor as it passes through the filter itself, as there has been little work done in this area of trickling filter performance.

Objectives

The primary objective of this study was to examine the interaction and relationship of hydraulic loading and organic loading through a small model trickling filter under varying conditions of loading.

It is hoped that the information thus obtained will be of use in the future design and operation of trickling filters and will, hopefully, give an insight into the actual physical processes which make up the workings of a trickling filter.

A secondary objective was to examine the variance of the pH of the waste water passing through the filter in both hydraulic and organic shock loadings in order to more reasonably predict what will happen and how to utilize the change in a real trickling filter.

CHAPTER II

LITERATURE SURVEY

General

Of all the process variables, the two that most directly control the growth of the microorganisms and the degree of treatment in the trickling filter environment are the hydraulic loading and the organic loading. For this reason, most research has been conducted in these two areas. Due to the great number of investigators and their varied techniques of obtaining information, there are many differences of opinion as to the method of application of the two parameters in the performance and evaluation of trickling filters.

There are two ways of treating hydraulic and organic loadings. The first is to consider the effects of each parameter separately and to assign to each a measure of importance in the treatment process. This method places emphasis upon the individual effects of the organic loading in milligrams per liter and the hydraulic rate of flow through the filter in gallons per day. The second method of evaluation considers the combined effects of both variables and incorporates them into a total organic loading factor, i. e., 200 mg/l at a hydraulic loading of 150 gpd/ft^2 is equal as far as total organics applied to 300 mg/l at a hydraulic loading of 100 gpd/ft^2.

It is the purpose of this chapter to review the relevant findings in the field and to present them in order to compare the two methods of parameter evaluation.

Separation of Parameters

Separating the process variables and assigning each one a particular amount of importance is the most common of the two methods of consideration. Investigators have known for a long time that certain variables of the trickling filter process possess more influence over the functioning of a filter than do others, and so, have tried to find the exact extent to which each factor exerts its influence.

The investigations into the effects of separate consideration reveal one basic agreement among the authorities, and that is the fact that the organic loading by itself is relatively insignificant. Several investigators have found that the organic loading level, usually expressed in mg/l, means little when it is considered to have a degree of influence. Schulze (24) maintains that the efficiency of a trickling filter at a given hydraulic load is not affected by the organic loading. Ingram (14) found that his results did not justify a conclusion that there was even a well-defined curve of removal efficiency with respect to loading. Grantham (9) states that the filter effluent deteriorates with high organic loading because nitrification of the effluent decreases as the organic loading increases. Fairall (6) indicates that the strength of the sewage in the filter feed is a negligible factor in filter performance when performance is evaluated as percent removal of BOD and within a range of values which does not limit the rate of oxygen absorption. Maier et al. (19) suggest that the mass transfer of the waste material in the feed to the slime layer in the trickling filter is the factor which controls the rate of usage with low-concentration feed, and Stack (28) agrees with the findings. Rankin (22) finds that the performance of the plants he studied appeared to be dependent upon one factor - the ratio of recirculation - and that dosing rate, loading of the filter, or filter depth had no significant effect.

Apart from the general agreement on the subject of organic loading's unimportance, there seems to be widespread disagreement regarding the parameter of hydraulic loading. Schulze (24), in working with a vertical screen filter, found that the controlling factor for efficiency was the hydraulic load. Maier et al. (19) assert that the hydraulic loading of the trickling filter is probably the most important process variable because it determines the thickness of the liquid film as well as the rate of nutrient addition. Eckenfelder (5) says that the time of contact within the filter bed is directly related to the hydraulic rate of flow for once-through treatment. Velz (30) supports the theory and says that the mass of zooglea in the bed and its sloughing, as well as the opportunity for and the period of contact, are dependent upon the hydraulic rate of flow of the liquid through the filter. Sinkoff et al. (26) showed that the mean residence time of a fluid flowing through a bed of loosely packed, unsaturated media is inversely proportional to the 0.83 power of the hydraulic loading for glass spheres and to the 0.53 power of the hydraulic loading for porcelain spheres. Keefer and Kratz (16) state that an increase in the rate of flow increases the BOD and decreases the nitrification of the effluent. Grantham (9) believes that hydraulic loading is important at high rates because the high flow tends to wash through the bed and distribute more equally the excess microorganisms which build up in the top layers due to a high percentage of assimilability. Bloodgood et al. (4) relate the degree of oxidation in the filter to the time of contact, which, in turn, is related to the hydraulic rate of flow.

Other investigators, however, have found that the hydraulic load does not significantly affect the performance of the trickling filter process. Keefer and Meisel (17) showed that increasing the hydraulic load by sevenfold brought a decrease in the BOD removal of only fifteen percent. Atkinson et al. (2), in performing a mathematical analysis of a flow model for bio-oxidation processes, concluded that the residence time analyses of trickling filters, which have been related to the hydraulic loading rate, are irrelevant. Ingram (14) observed that the hydraulic flow rate through the filter was not the controlling factor; rather, his studies suggest that the relationship between the oxygen supply and the BOD loadings is of greater importance. Abdul-Rahim et al. (1) indicate that the percent reduction in 5-day BOD does not change with an increase in the hydraulic load in the 10 to 30 MGAD range, but that a decrease in the percent reduction did occur when the loading was greater than 30 MGAD. They also note that the percent reduction in BOD is the same at all the hydraulic loading rates at a specific depth. Galler and Gotaas (7) believe that the introduction of recirculation makes the effect of hydraulic loading insignificant and have shown this to be true by regression analyses. They do concede, however, that in most cases, the amount of BOD applied to a filter is reflected by the hydraulic rate, i. e., high hydraulic rates are indicative of high organic loadings.

Combination of Parameters

The second method of dealing with the factors of organic and hydraulic loading is to combine them into a single term, giving both the same measure of importance, and considering the loading to the filter to be in terms of total organic loading; that is, a high rate of relatively low-concentration waste through the filter is treated in the same way as a low flow rate of relatively high-concentration waste, because the total organics applied to the filter per day are the same.

The National Research Council's formula (23), the first such formula to be widely published, includes a term which considers total organic loading per 1000 cubic feet of filter volume. Ingram (14) observes that the BOD removal produces about the same efficiency with the same loading regardless of whether the loading is accomplished by a higher flow rate of weaker sewage or a lower flow rate of stronger sewage. Abdul-Rahim et al. (1) reported that an important factor in the design of trickling filters is the actual pounds of BOD removed per 1000 cubic feet of the filter volume.

In the present research, an attempt was made to gain a better understanding of the role of each of the two major parameters and to compare the findings with what is already known but widely disputed.

CHAPTER III

THEORETICAL CONSIDERATIONS

General

Much of the disagreement concerning the lack of homogeneity in the treatment and efficiency of the trickling filter process stems from the varied methods employed by investigators to examine its variables. This is especially true of the hydraulic loading rate and the organic loading level because they constitute the two most basic controlling parameters of the process. Due to the widespread techniques of examination, there have developed a great number of formulae to be used in the design and operation of trickling filters, but of all the work done there appear to be five equations - those of the National Research Council, Velz, Howland, Eckenfelder, and Galler-Gotaas - which most accurately represent the occurrences within the filter bed. Herein will be presented briefly the theory behind each formulation, with special emphasis placed upon the development of the organic and/or hydraulic loading terms, to which the findings from the model trickling filter may be compared.

The National Research Council Formula

In 1946 the Sub-Committee on Sewage Treatment in Military Installations of the National Research Council examined the treatment facilities of the 34 Army and Navy installations in this country which utilized trickling filter and activated sludge types of treatment and, based upon this study, proposed a formula for the design of trickling filters of the form:

$$E = \frac{1}{1 + C\left(\frac{w}{VF}\right)^{0.5}}$$

where: E = efficiency of the filter

w = organic loading

V = filter volume

F = recirculation factor

It is not readily apparent, but the National Research Council (NRC) Formula combines the effect of hydraulic and organic loadings into one term, to be considered as the total organic loading applied to the filter. This is the term designated "w" in the equation and is the product of the organic loading, the hydraulic loading, and the proper coefficients to create the units of pounds of organics per 1000 ft^3 of filter volume or of pounds of organics applied per day. In this form, neither the organic nor the hydraulic loading is given primary importance, but rather both are to be considered equally, and it is to be assumed that a high rate of flow through the filter of low-concentration sewage will be treated in the same way as a low rate of flow of high-concentration sewage. Thus, the NRC Formula relates both parameters to the removal efficiency.

The Velz Formula

The formula proposed by C. J. Velz was the first of the first-order equations; that is, it is assumed that the reaction between the waste and the microorganisms in the filter environment is a first-order reaction. Velz proposed that the depth rate of extraction of organic matter is proportional to the remaining concentration of organic matter, or:

$$\frac{dL}{dD} = -KL$$

which integrates to:

$$\frac{L_e}{L_o} = e^{-KD}$$

where: L_e = BOD in the effluent

L_o = BOD applied in the influent

D = depth of the filter

The importance of the Velz Formula lies in the assumption of first-order kinetics rather than in a clarification of the relationship between hydraulic and organic loading because it presents for the first time an equation which takes into account the microbial nature of the trickling filter process. It is, to be sure, an assumption, but it began the search for the answer to trickling filter performance in the light of the microorganisms contained within the filter rather than a formula dependent upon the strict application of process variables such as organic loading and hydraulic loading in the NRC Formula.

The Howland Formula

W. E. Howland proposed a formula based upon Velz' assumption of first-order kinetics, but Howland suggested that the time rate rather than the depth rate of extraction was proportional to the amount of BOD remaining, or:

$$\frac{dL}{dt} = -KL$$

which integrates to:

$$\frac{L_e}{L_o} = e^{-Kt}$$

where L_e = BOD in the effluent

L_o = BOD applied in the influent

t = time

Howland was interested in the time of contact between the micro-organisms in the filter and the waste applied to it. He found that the time of contact, or residence time, was related to the hydraulic rate of flow through the filter and to the depth of the filter in the following manner:

$$t = \frac{K'D}{Q^n}$$

where: D = depth of the filter

Q = hydraulic rate of flow through the filter

n = exponent

Howland also provided a correction factor, Θ, to allow for a change in temperature, and by substituting both the above factors into the integrated formula, arrived at his final form:

$$\frac{L_e}{L_o} = e^{-K\Theta\,(D/Q^n)}$$

Howland's interest in the time of contact led to a relationship between the removal efficiency of a filter and the hydraulic rate of flow through it, but this has been shown to apply only in the case of once-through treatment (7). The addition of recirculation causes the relationship to break down. Nevertheless, it is clear that Howland considers the parameter of organic loading to be independent; that is, the efficiency of a trickling filter at a given hydraulic loading is independent of the organic load placed upon it.

The Eckenfelder Formula

Wesley W. Eckenfelder developed his equation in accordance with the work of Velz, Howland, and Schulze on the assumption of first-order time rate of removal. However, Eckenfelder added the effect of non-homogeneity of removal with respect to depth, and in its final form his equation is:

$$L_e = \frac{L_o}{1 + K\left(\frac{D^{1-m}}{Q^n}\right)}$$

where: L_e = BOD in the effluent

L_o = BOD applied in the influent

D = depth of the filter

Q = hydraulic rate of flow through the filter

$(1-m)$ = exponent, zero when the biological growth is uniformly distributed with depth

Eckenfelder, too, suggests that the time of contact in the filter is related to the hydraulic rate of flow, and, therefore, to the amount of treatment obtained. Eckenfelder altered the equations of Velz and Howland because they considered all portions of the filter liquor to be equally assimilable. The net effect of the Eckenfelder equation is to apply a retardant function, taking into account the fact that the more readily assimilable components will be removed more rapidly, but the main concern is that the removal is related to the hydraulic loading.

<u>The Galler-Gotaas Formula</u>

The equation of Galler and Gotaas represents theoretical work with regression analyses. They evaluated the data from many experimental filters, including the effects of each individual process variable and found mathematically the best value of regression correlation to be:

$$L_e = \frac{0.464\ L_o^{1.19}\ (1 + R)^{0.28}\ (Q/A)^{0.13}}{(1 + D)^{0.67}\ T^{0.15}}$$

where: L_e = BOD in the effluent

L_o = BOD applied in the influent

R = recirculation ratio

Q = hydraulic loading

A = area of the filter

D = depth of the filter

T = temperature of the filter liquor

In their work with regression analyses, Galler and Gotaas deleted the hydraulic loading term on the assumption that, because of recirculation, the hydraulic loading term would become unimportant. The regression coefficient of the formula without the hydraulic rate very closely approximated the coefficient of the formula where it was considered, and this led the investigators to conclude that the inclusion of a recirculation term definitely affects the way in which hydraulic loading is considered.

CHAPTER IV

APPARATUS AND PROCEDURE

Apparatus

The general arrangement of the experimental trickling filter system is shown in Figure 1. The filter bed itself is composed of several cubic plexiglas units filled with stone, each unit being 1.0 foot on each side and enclosing a volume of 1.0 cubic foot. The units may be stacked to give any reactor depth desired, while the surface area of the bed is 1.0 square foot. For the purposes of this experiment, the depth of the filter was maintained at four feet. Each individual unit is open at the top; the bottom is a grid of plastic strips used to support the stones and has enough sufficiently large openings within the grid to allow free percolation of waste water through the filter. The stones within each unit are from an old trickling filter and are varied in size from one inch to three inches in diameter.

The units are stacked atop each other with a three-inch spacer collar between each unit. This spacer is provided with sampling ports through which samples may be collected for analysis, thus enabling one to sample at each foot of depth without disturbing the internal workings of the filter itself. The only drawback to this method is that it allows an excess of free circulation of air throughout the depth of the filter that would not ordinarily present itself in an actual filter.

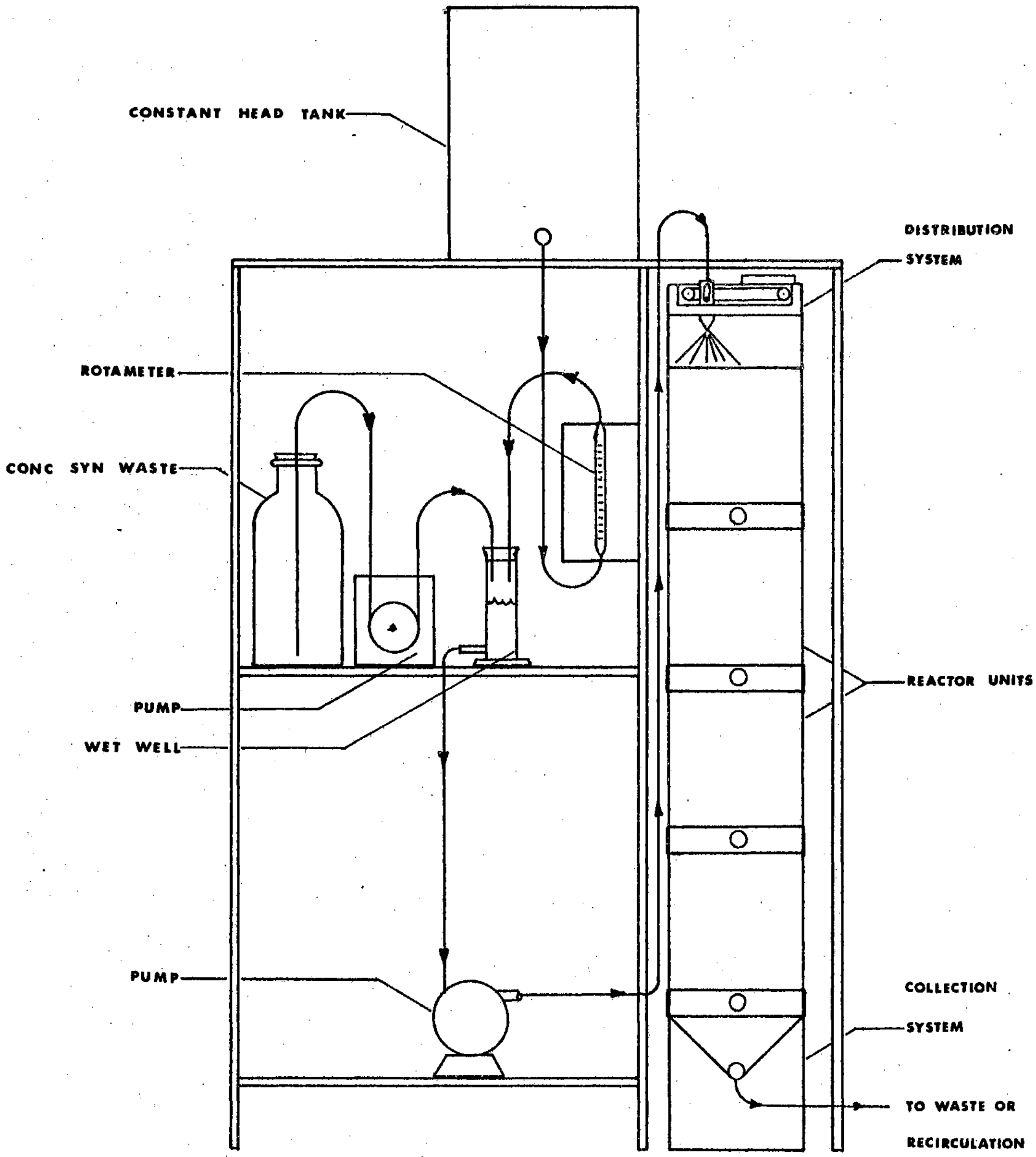

Figure 1. Schematic Drawing of the Experimental Trickling Filter Layout

Tap water from the city main of Stillwater enters a constant head tank, necessary in order to provide for accurate calibration of metering devices. The flow from the tank is regulated by either of two rotameters, one of which is capable of handling flows of from 75 to 150 gallons per day and the other of from 150 to 1000 gallons per day. After metering, the tap water flows into a wet well in order to mix with concentrated synthetic feed, the components of which are given in Table I. The synthetic feed is made up in concentrations sufficient to produce the desired chemical oxygen demand for each flow rate and is then fed into the wet well by means of a Sigmamotor pump. The pump is set so as to completely empty the container of feed in 24 hours, thereby producing a constant daily feed rate. It is obvious, then, that to change the chemical oxygen demand of the system, one has merely to change the concentration of feed to the unit.

After mixing in the wet well, the combined feed/water mixture is then pumped to the distribution nozzle. Two pumps were employed in order to facilitate the changeover from one flow rate to another. When a new flow rate was called for, the second of the two pumps was put into use, the first being taken out of operation, chlorinated, rinsed, and readied for the next higher flow rate. In this manner there was a fresh pump each time the rate was changed, with no down time for chlorination and cleaning. In chlorinating the pump, the distribution line leading to the nozzle was also treated in order to kill any microorganisms present, thereby helping to prevent clogging of the distribution nozzle. All chlorination was accomplished with approximately a ten percent solution of free available chlorine.

The distribution system for applying the waste water to the reactor

TABLE I

COMPOSITION OF CONCENTRATED SYNTHETIC FEED

Ingredient	Minimal Feed for 100 gal.	Stock Solution
Sucrose	100 mg/l	---
Ammonium sulfate $(NH_4)_2 SO_4$	25 mg/l	500 gm/lit
Magnesium sulfate $Mg SO_4 \cdot 7 H_2O$	10 mg/l	500 gm/lit
Ferric chloride $Fe Cl_3$	0.5 mg/l	50 gm/lit
Manganous sulfate $Mn SO_4 \cdot H_2O$	1.0 mg/l	200 gm/lit
Calcium chloride $Ca Cl_2 \cdot 2 H_2O$	0.75 mg/l	600 gm/lit
Potassium biphosphate $K_2 H PO_4$	6.0 mg/l	500 gm/lit

bed itself was accomplished by means of an oscillating spray nozzle. The nozzle is powered by an electric motor via chain drive and approximates a constant linear velocity at any selected speed of 20-54 ft/min. The spray pattern, then, becomes a rectangular band approximately 12 inches long and 3½ inches wide whose dimensions may be varied simply by raising or lowering the nozzle to achieve the desired spray pattern dimensions. By interchanging nozzles and increasing or decreasing the pump rate, the flow rate through the nozzle may be varied, allowing for the investigation of both the hydraulic loading and the dosing frequency to the filter.

At the bottom of the last box was a collection device which drained the effluent into a nearby sump, but which had sufficient space so as to be able to sample the effluent. The results, then are for once-through treatment with no recirculation.

Procedure

It was the primary purpose of this experiment to investigate the relationship of hydraulic and organic loading to trickling filter performance and efficiency. Consequently, a matrix involving both parameters was arranged. In order to keep the model filter within the range of a standard-rate trickling filter, it was decided that the hydraulic loadings would be 75, 100, 150, and 200 gallons per day per square foot (gpd/ft^2) and that the organic parameters would be 100, 150, 200, and 300 milligrams per liter (mg/l) COD. The procedure would be to start at the lowest hydraulic flow rate and the lowest organic loading level and to vary the hydraulic loadings throughout their range. In other words, a COD level of 100 mg/l would be maintained while varying the hydraulic loading from 75 to 100 to 150 to 200 gpd/ft^2. When one organic level was completed, the organic level would be raised, the hydraulic loadings varied, and so on. In this way the whole matrix of hydraulic and organic loadings could be studied and compared to see which organic or hydraulic loading, if, indeed, any, would result in better performance or higher efficiency of the filter. It would also give several comparable combinations of total organic loadings, i. e., 200 mg/l at 150 gpd/ft^2 would be equal as far as total organics to 300 mg/l at 100 gpd/ft^2. In this manner, one could judge the performance of the filter by total organic removal instead of percent removal of COD.

At the beginning of the experiment the bed of the reactor had no biological growth. An initial seeding of sewage from the primary clarifier of the Stillwater sewage treatment plant was applied and the feeding process begun with the feed concentration at 100 mg/l and a flow rate of 75 gpd/ft^2. From time to time additional fresh sewage seed was added until it was felt that the growth was sufficient to begin experimentation. This period of time was about two weeks.

After this start-up time, the experiment was begun at the loadings stated above. Each day samples were taken at the nozzle and at each foot of depth, filtered through a Millipore filter and frozen until ready for use. At the outset of the experiment it was not known how long the experimental filter would take to come to equilibrium after changing flow rates, so samples were taken each day in the beginning to determine the approximate number of days the filter required. It was found that after about four days the filter had reached sufficient equilibrium to carry out the necessary tests, and in later tests, after the filter flow rate was changed, the only tests run were on the third and fourth days of operation in order to assure that equilibrium had been reached or very closely approximated. Most of the test runs agreed closely in their third- and fourth-day data.

Also a matter of interest was the change in pH of the filter liquor as it traveled through the filter. Each day a small sample of the waste water was taken at the nozzle and at each foot of depth the pH was taken, and the readings were recorded. The pH readings were always on samples taken directly from the experimental filter itself and were not filtered or altered in any way. In this way a continuous record of the change in pH through the filter was made, including the effects of hydraulic shock loads when the hydraulic rate was raised during each organic loading level, as well as the effect of combined hydraulic and organic shock loads when the end of a series of hydraulic raises was reached and the next higher organic level was begun. It is felt that this contribution of pH change throughout the range of loadings of the filter may help to further explain the nature of the trickling filter process.

Analytical Procedures

Filtrate COD was determined in accordance with the procedures given in Standard Methods (29).

pH was taken as the value read from a Beckman Zeromatic II pH Meter in accordance with the procedure outlined in the Beckman Operating and Maintenance Instruction Manual (3).

CHAPTER V

RESULTS

Consideration of Individual Effects

In order to completely cover the matrix of hydraulic and organic loadings, a total of sixteen runs was required, the results of which are tabulated in Table II. It will be noted that each component of the matrix, that is, each ordered pair of one hydraulic loading and one organic loading level, is subdivided to show the results of the COD runs performed upon it, the corresponding total organic loadings and the percentages of both COD and total organics remaining at the various feet of depth of the filter.

This table provides a quick check of the characteristics of the model trickling filter, in that one may compare the efficiencies of the filter while under a constant hydraulic load, a constant organic load, or at similar total organic loadings.

Figure 2 is a typical graph of the percent COD remaining at each foot of depth. The two lines of the graph represent the values obtained on the third and the fourth day after changing the flow rate, as discussed previously. The data shown are for an organic level of 200 mg/l and a hydraulic loading rate of 150 gpd/ft^2 through the filter but are characteristic of each of the organic and hydraulic loading combinations.

In order to evaluate the effects of organic loading and hydraulic loading separately, the data were grouped and plotted accordingly.

TABLE II

SUMMARY OF TRICKLING FILTER PERFORMANCE

	75 gpd/ft^2				100 gpd/ft^2				150 gpd/ft^2				200 gpd/ft^2			
	Depth (ft.)	COD Remain. (mg/l)	T. O. Remain. (lb/day/ft^2)	% Remain.	Depth (ft.)	COD Remain. (mg/l)	T. O. Remain. (lb/day/ft^2)	% Remain.	Depth (ft.)	COD Remain. (mg/l)	T. O. Remain. (lb/day/ft^2)	% Remain.	Depth (ft.)	COD Remain. (mg/l)	T. O. Remain. (lb/day/ft^2)	% Remain.
	0	103.0	0.064	100.0	0	114.4	0.095	100.0	0	109.8	0.137	100.0	0	115.4	0.192	100.0
100	1	65.5	0.041	64.1	1	83.6	0.070	73.7	1	90.6	0.113	82.5	1	86.5	0.144	75.0
mg/l	2	32.2	0.020	31.3	2	39.6	0.033	34.7	2	57.7	0.072	52.5	2	72.1	0.120	62.5
	3	27.0	0.017	26.6	3	28.6	0.024	25.3	3	57.7	0.072	52.5	3	45.4	0.082	42.7
	4	20.8	0.013	20.3	4	19.8	0.016	16.8	4	30.9	0.039	28.5	4	78.3	0.130	67.7
	0	163.0	0.102	100.0	0	158.4	0.132	100.0	0	155.9	0.195	100.0	0	153.0	0.255	100.0
150	1	103.7	0.065	63.7	1	99.0	0.082	62.1	1	114.2	0.143	73.3	1	124.5	0.207	81.2
mg/l	2	67.3	0.042	41.1	2	88.0	0.073	55.3	2	105.4	0.132	67.7	2	99.8	0.166	65.1
	3	44.5	0.027	26.5	3	66.0	0.055	41.7	3	98.8	0.123	63.1	3	90.3	0.150	58.8
	4	28.5	0.018	17.6	4	45.1	0.038	28.8	4	52.7	0.066	33.8	4	82.7	0.138	54.1
	0	235.6	0.147	100.0	0	201.4	0.168	100.0	0	210.5	0.263	100.0	0	193.0	0.322	100.0
200	1	167.2	0.104	70.7	1	148.2	0.123	73.2	1	163.0	0.204	77.6	1	167.2	0.279	86.6
mg/l	2	146.3	0.091	61.9	2	133.0	0.111	66.1	2	146.5	0.183	69.6	2	130.0	0.217	67.4
	3	144.4	0.090	61.2	3	98.8	0.082	48.8	3	109.4	0.137	52.1	3	99.1	0.165	51.2
	4	186.2	0.116	78.9	4	77.9	0.065	38.7	4	79.5	0.099	37.6	4	117.6	0.196	60.9
	0	321.3	0.201	100.0	0	304.5	0.254	100.0	0	349.7	0.437	100.0	0	293.4	0.489	100.0
300	1	240.5	0.150	74.6	1	241.5	0.201	79.1	1	271.4	0.339	77.6	1	250.9	0.418	85.5
mg/l	2	185.9	0.116	57.7	2	205.8	0.171	67.3	2	269.3	0.336	76.9	2	216.2	0.360	73.6
	3	186.9	0.117	58.2	3	170.1	0.142	55.9	3	227.1	0.284	65.0	3	191.1	0.318	65.0
	4	117.6	0.073	36.3	4	144.9	0.121	47.6	4	150.8	0.188	43.0	4	154.4	0.257	52.6

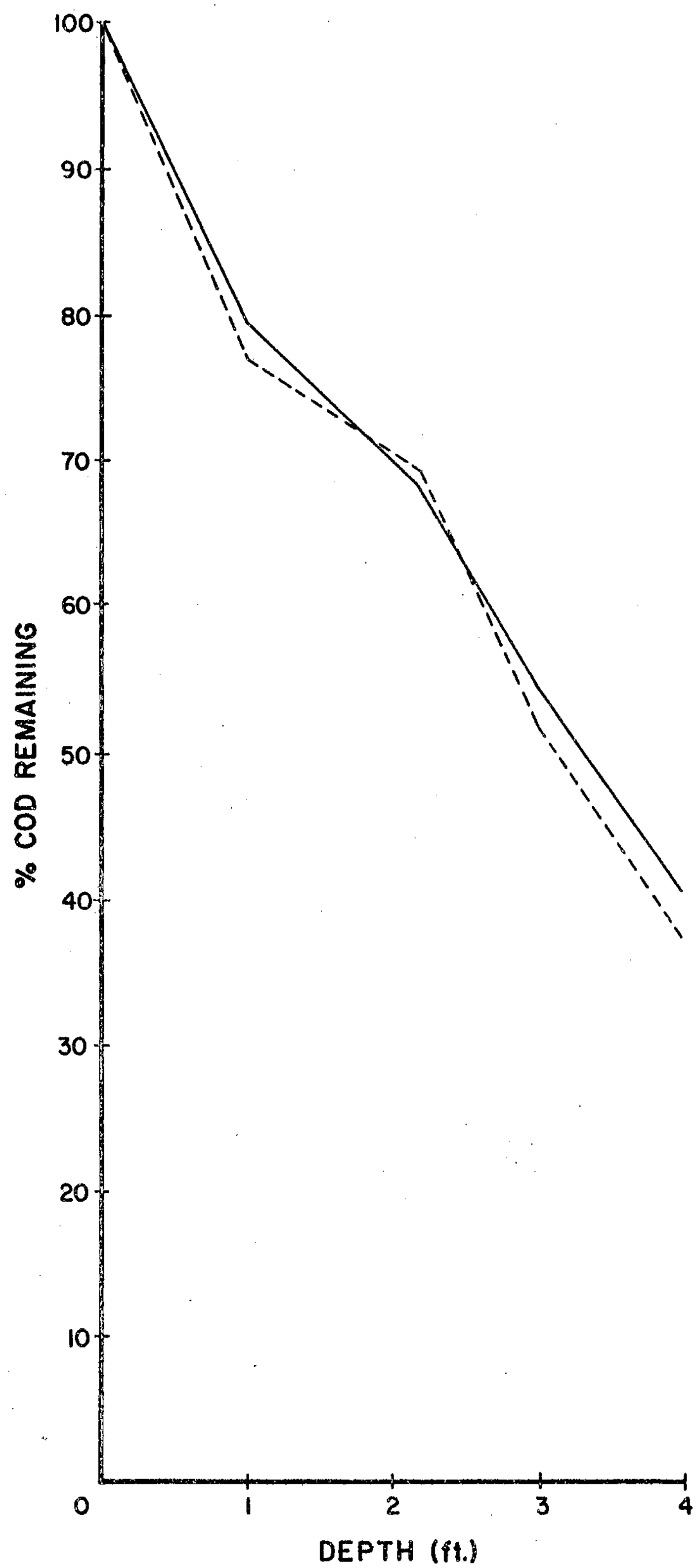

Figure 2. Typical Plot of the Percent COD Remaining Versus the Depth of the Filter

Figures 3 through 6 are composite graphs of the percent COD remaining at each foot of depth of the filter plotted under conditions of constant organic loading, and Figures 7 through 10 are graphs of the same parameters plotted under conditions of constant hydraulic loading. The two lines on each plot represent the data obtained on the third and fourth days after a change in flow rate or a change in both flow rate and organic loading. It will be noticed that both sets of composite plots exhibit the same characteristics; that is, at a constant organic level, the percent COD remaining in the filter at each foot of depth increases with increasing hydraulic loading, and at a constant hydraulic loading rate, the percent COD remaining in the filter at each foot of depth increases with increasing organic load. It is thus implied that neither of the two parameters is independent of the other within the range of this study and that both are to be considered critical factors in the operation of the trickling filter process.

Properties of Similar Total Organic Loadings

With this in mind, the data were grouped according to similar total organic loading properties. The total organic loading is a parameter which expresses the amount of biodegradable matter that is applied to the filter per unit of time rather than per unit of filter liquor volume and which takes into account both the organic loading and the hydraulic loading rate. Total organic loading is found by multiplying the organic and hydraulic rates and then converting them by use of the proper coefficients into units of amount of matter applied per time interval, in this case, pounds of COD applied per day. It is obvious, then, that an organic loading of 150 mg/l at a hydraulic loading of 200 gpd/ft^2 is

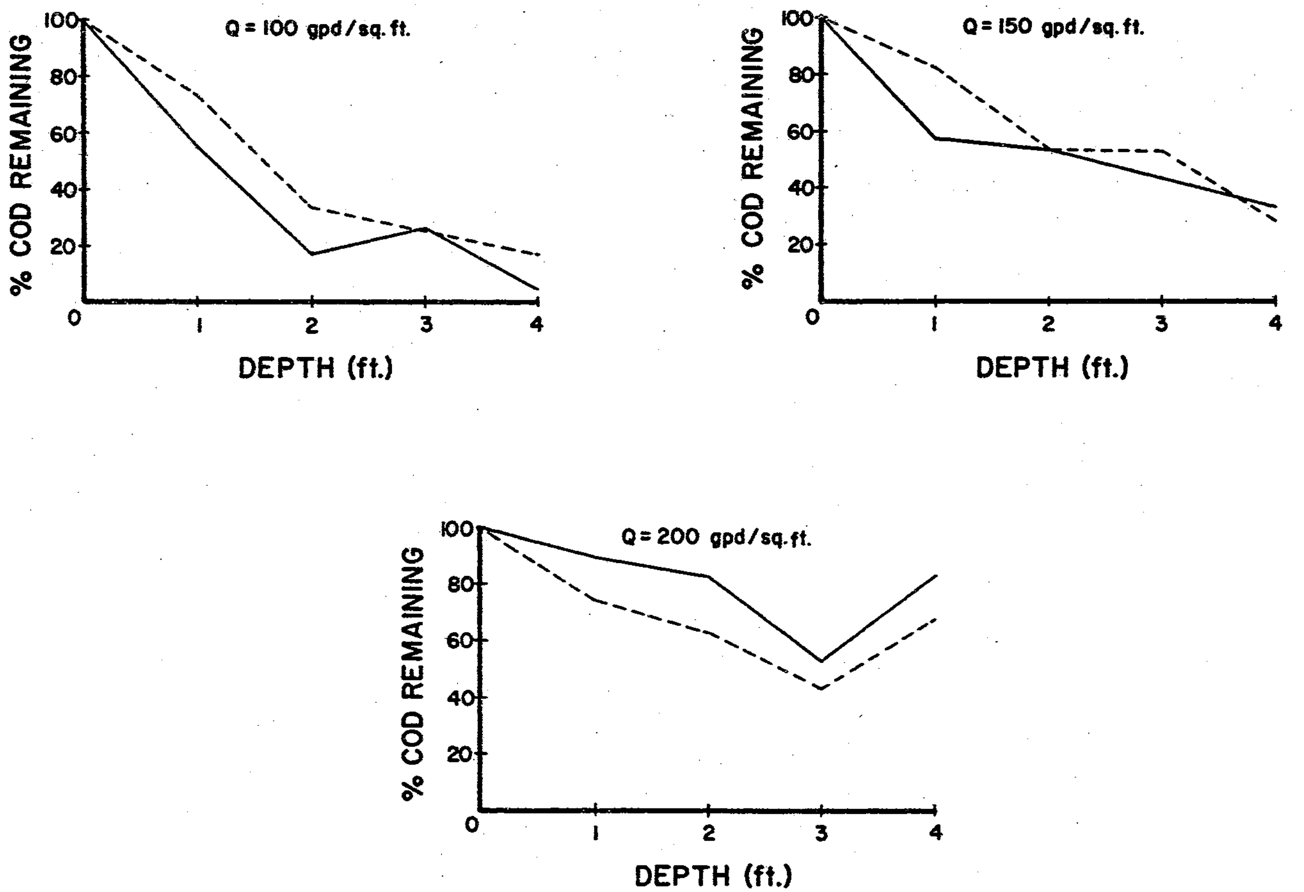

Figure 3. Percent COD Remaining vs. Depth Under a Constant Organic Loading of 100 mg/l

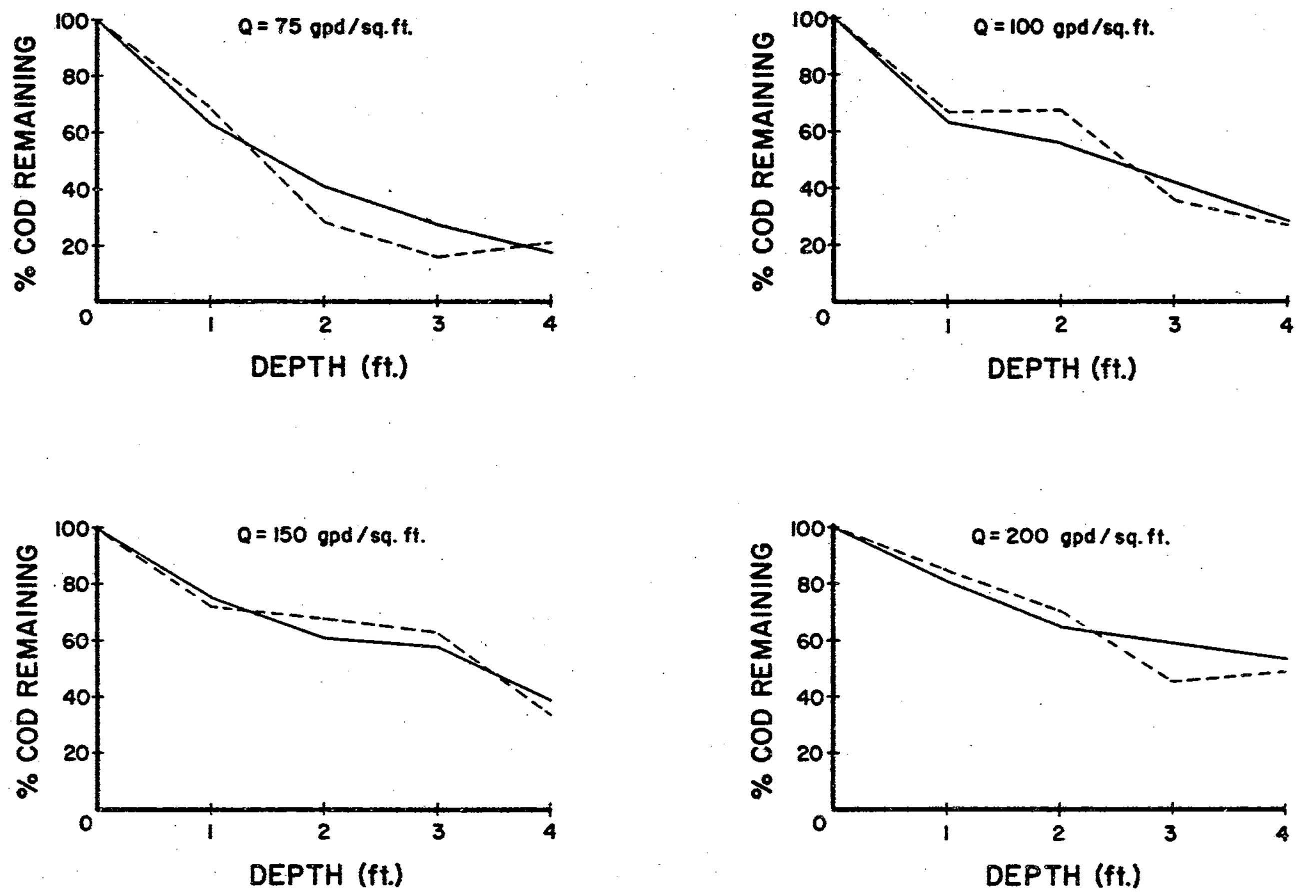

Figure 4. Percent COD Remaining vs. Depth Under a Constant Organic Loading of 150 mg/l

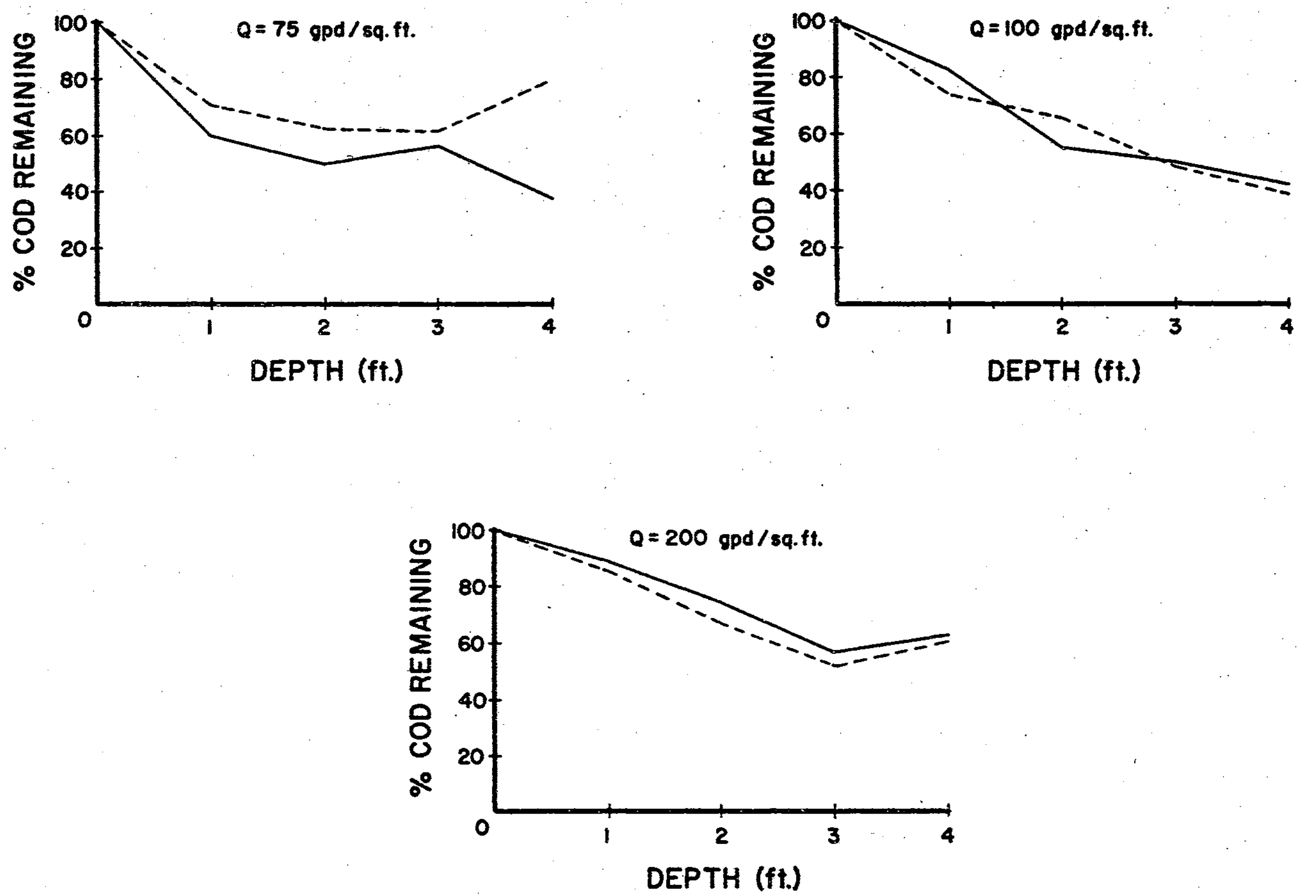

Table 5. Percent COD Remaining vs. Depth Under a Constant Organic Loading of 200 mg/l

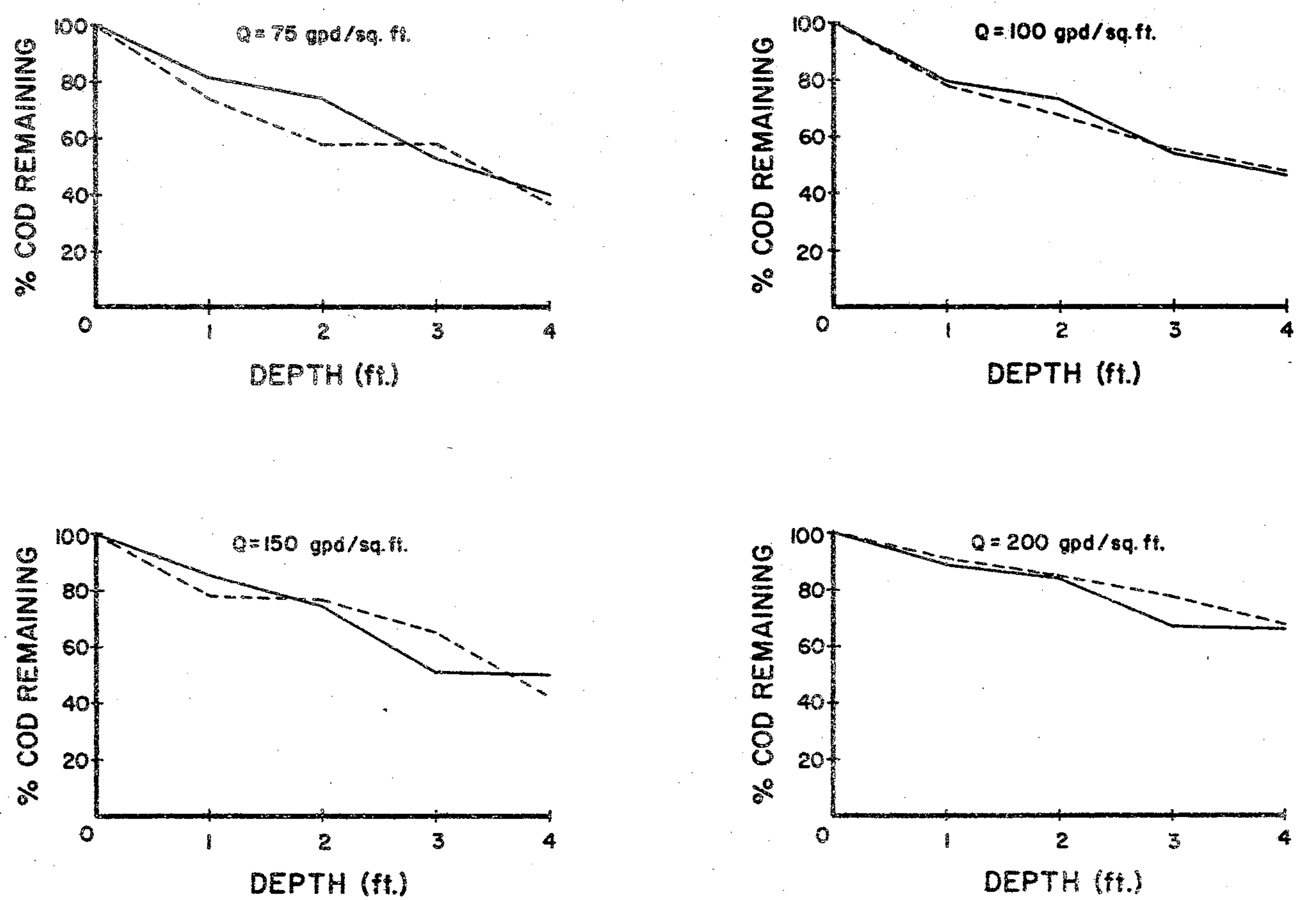

Figure 6. Percent COD Remaining vs. Depth Under a Constant Organic Loading of 300 mg/l

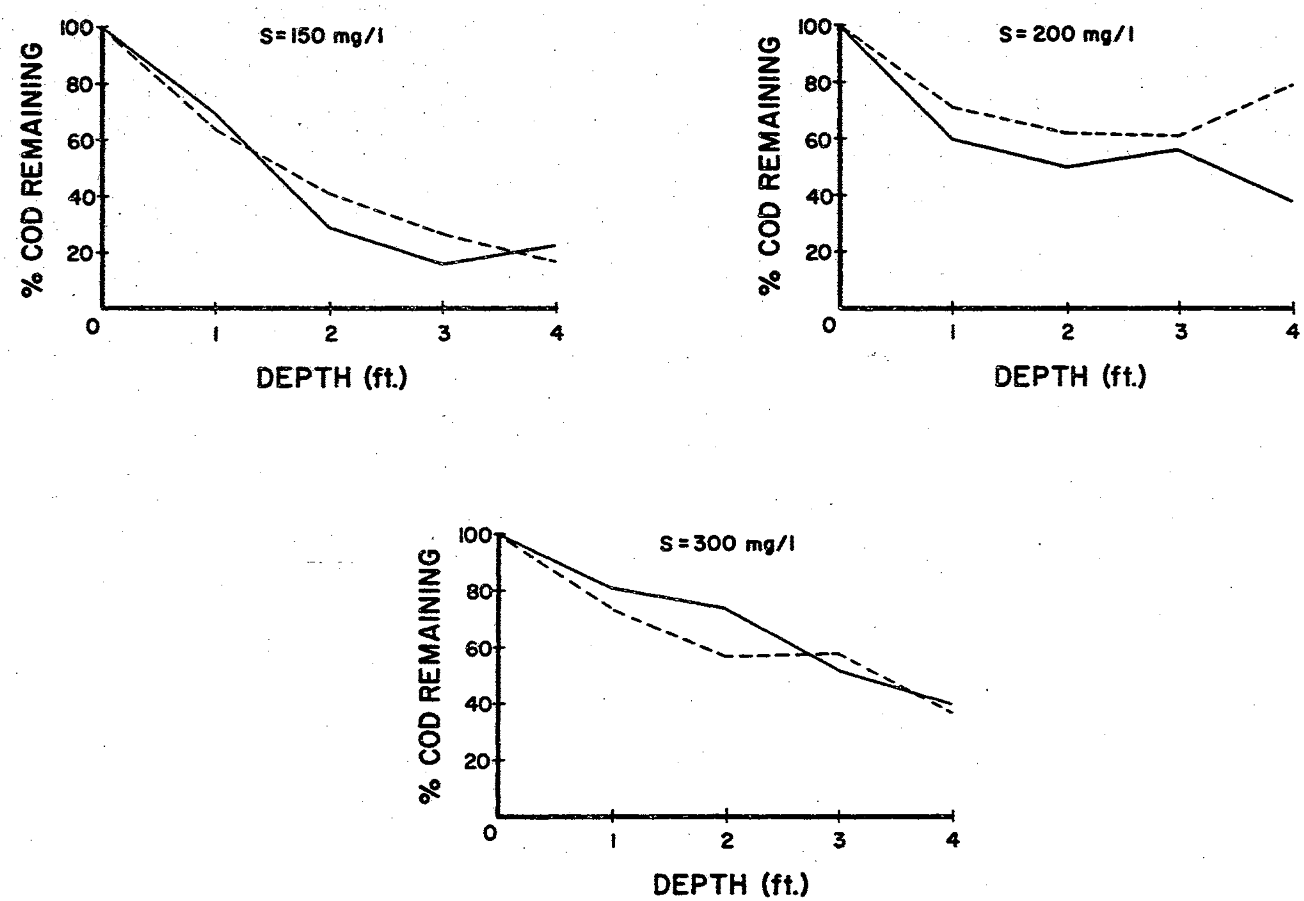

Figure 7. Percent COD Remaining vs. Depth Under a Constant Hydraulic Loading of 75 gpd/sq.ft.

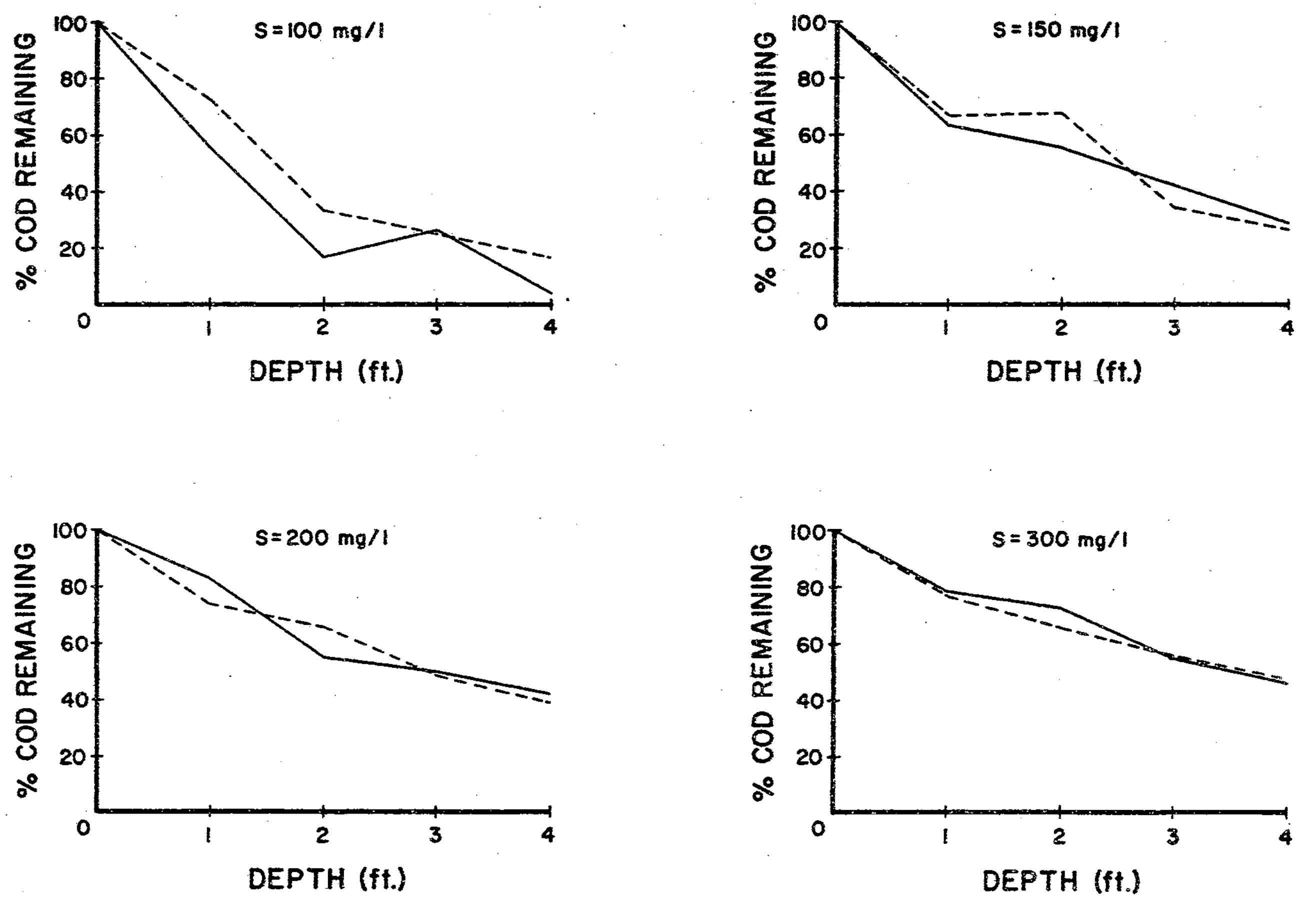

Figure 8. Percent COD Remaining vs. Depth Under a Constant Hydraulic Loading of 100 gpd/sq. ft.

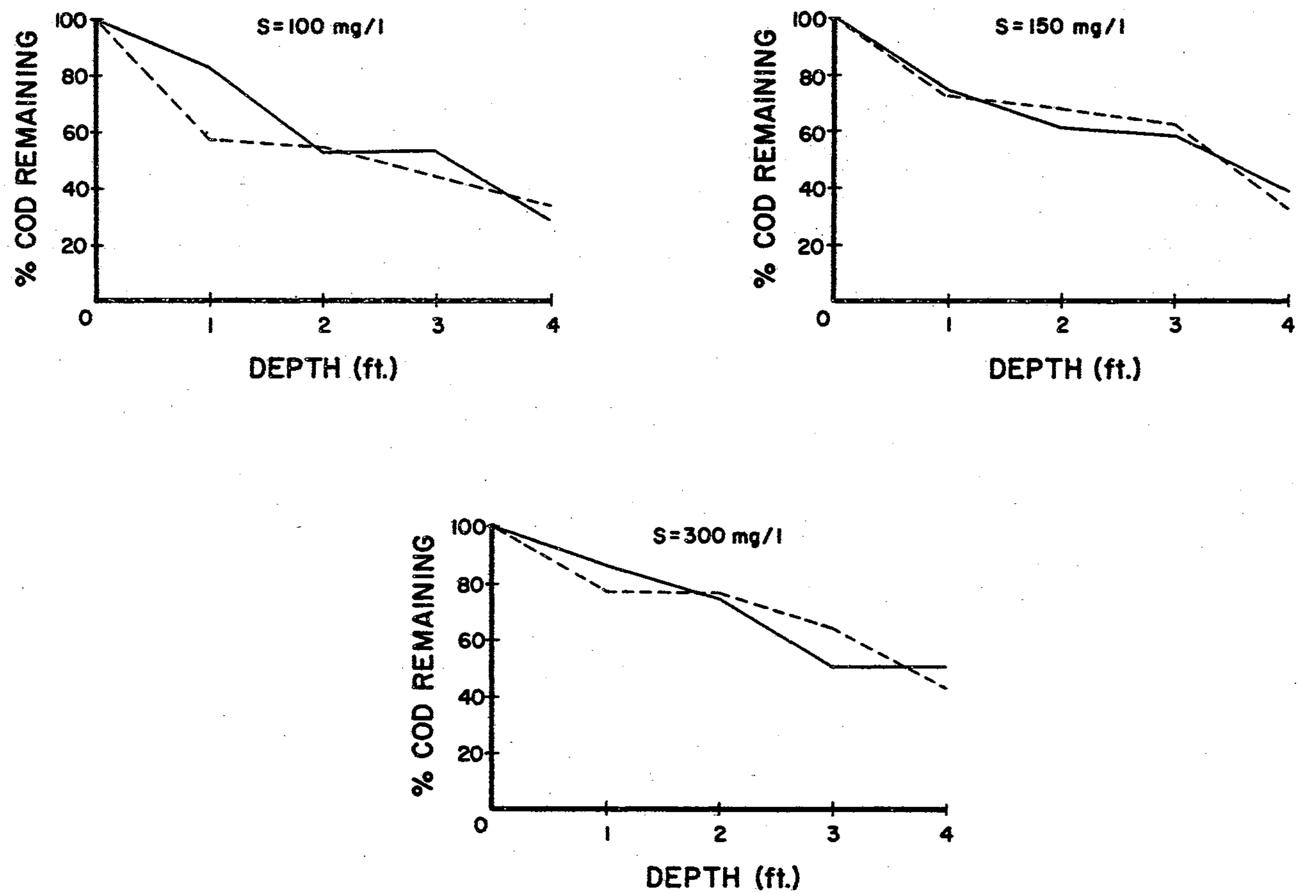

Figure 9. Percent COD Remaining vs. Depth Under a Constant Hydraulic Loading of 150 gpd/sq. ft.

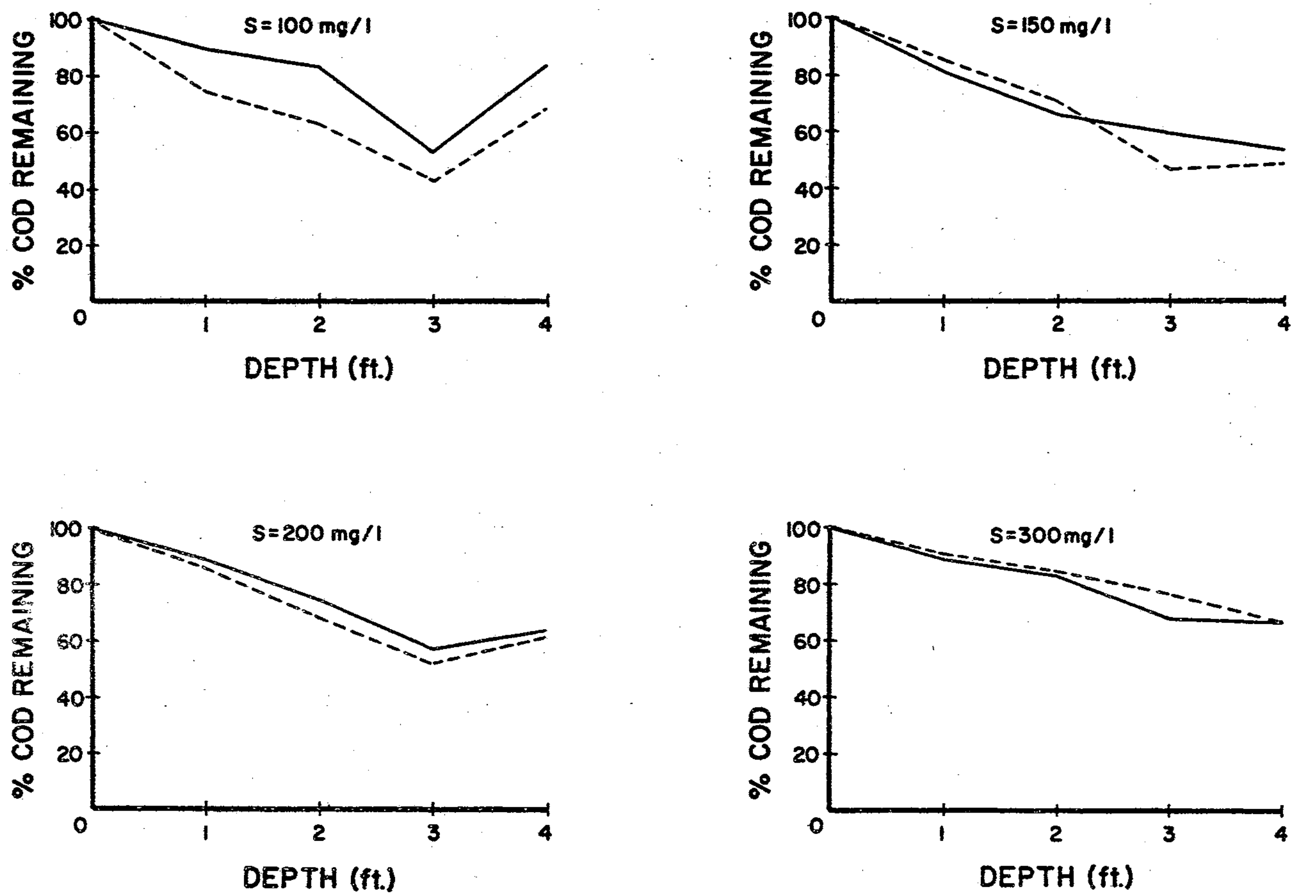

Figure 10. Percent COD Remaining vs. Depth Under a Constant Hydraulic Loading of 200 gpd/sq. ft.

to be considered equal to an organic loading of 100 mg/l at a hydraulic loading of 300 gpd/ft^2. This places equal emphasis upon both parameters and permits examination of the filter performance with respect to the total amount of organics applied.

Upon examination of the matrix of organic and hydraulic loadings selected for this experiment, it was apparent that there would be available several equal or very nearly equal total organic loads. For example, although 100 mg/l at 100 gpd/ft^2 is not exactly equal to 150 mg/l at 75 gpd/ft^2, the two are very close and should be inspected together. The same nearness is found in considering 100 mg/l at 200 gpd/ft^2 and 150 mg/l at 150 gpd/ft^2, and these, too, were grouped together for the purposes of comparison.

It will be noticed from the data in Table III that equal or very nearly equal total organic loads applied to the top box of the experimental trickling filter produced approximately equal total organic removal throughout each foot of depth of the filter, regardless of the variation in either organic loading or hydraulic loading by themselves. At the same time, the percent removal efficiencies of each foot of depth compare favorably when total organic loading is the basis for comparison. Group IV illustrates the concept for a total organic loading of 0.25 lb/day, which corresponds to 100 gpd/ft^2 at 300 mg/l, 150 gpd/ft^2 at 200 mg/l, and 200 gpd/ft^2 at 150 mg/l. The hydraulic and organic loadings are different and vary widely through the sequence; however, the total organics remaining at each foot of depth and the removal efficiencies at each foot of depth are quite close to each other.

Figure 11 is a plot of the percent total organics remaining against the amount of total organics applied. From the graph it is seen that

TABLE III

COMPARISON OF COMPARABLE TOTAL ORGANIC LOADING REMOVAL

Group I

	gpd/ft^2	mg/l	Depth 0'	1'	2'	3'	4'
lb/day Remaining	75	150	0.102	0.065	0.042	0.027	0.018
	100	100	0.095	0.070	0.033	0.024	0.016
% Organics Remaining	75	150	100.0	63.7	41.1	26.5	17.6
	100	100	100.0	73.7	34.7	25.3	16.8

Group II

	gpd/ft^2	mg/l	Depth 0'	1'	2'	3'	4'
lb/day Remaining	75	200	0.147	0.104	0.091	0.090	0.116
	100	150	0.132	0.082	0.073	0.055	0.038
	150	100	0.137	0.113	0.072	0.072	0.039
% Organics Remaining	75	200	100.0	70.7	61.9	61.2	78.9
	100	150	100.0	62.1	55.3	41.7	28.8
	150	100	100.0	82.5	52.5	52.5	28.5

Group III

	gpd/ft^2	mg/l	Depth 0'	1'	2'	3'	4'
lb/day Remaining	75	300	0.201	0.150	0.116	0.117	0.073
	100	200	0.168	0.123	0.111	0.082	0.065
	150	150	0.195	0.143	0.132	0.123	0.066
	200	100	0.192	0.144	0.120	0.082	0.130
% Organics Remaining	75	300	100.0	74.6	57.7	58.2	36.3
	100	200	100.0	73.2	66.1	48.8	38.7
	150	150	100.0	73.3	67.7	63.1	33.8
	200	100	100.0	75.0	62.5	42.7	67.7

Group IV

	gpd/ft^2	mg/l	Depth 0'	1'	2'	3'	4'
lb/day Remaining	100	300	0.254	0.201	0.171	0.142	0.121
	150	200	0.263	0.204	0.183	0.137	0.099
	200	150	0.255	0.207	0.166	0.150	0.138
% Organics Remaining	100	300	100.0	79.1	67.3	55.9	47.6
	150	200	100.0	77.6	69.6	52.1	37.6
	200	150	100.0	81.2	65.1	58.8	54.1

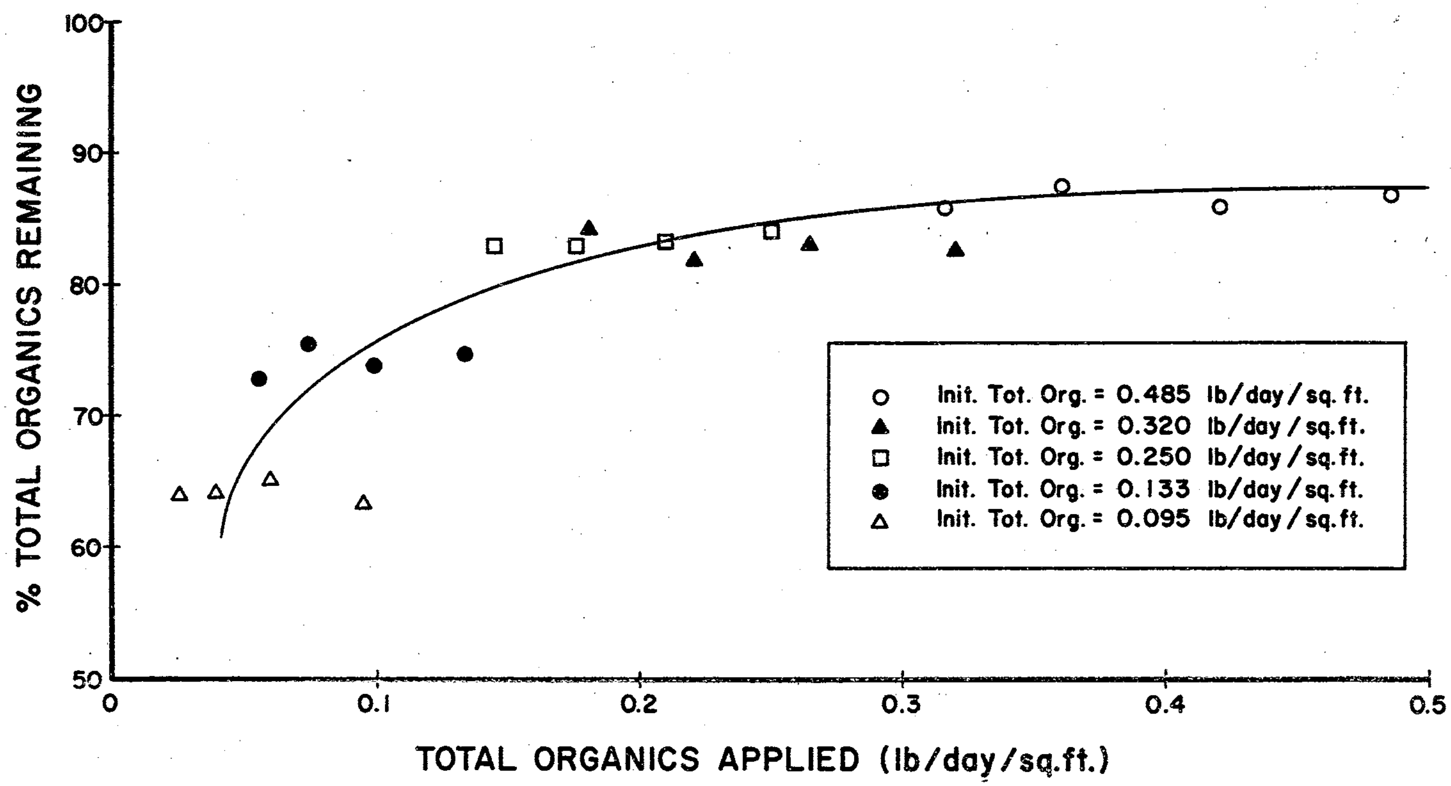

Figure 11. Percent Total Organics Remaining vs. Total Organics Applied

there is a tendency toward saturation; that is, it appears that at very low total organics levels, say, below 0.2 lb/day/ft^2, the percent total organics remaining fluctuates sharply when the amount of total organics is varied, but at higher total organic levels, say, above 0.3 lb/day/ft^2, there is a tendency of the system to remove a constant percentage of the organics applied. This implies that at higher total organic loadings there is a constant percentage above which the filter will not remove, this limiting value being the maximum efficiency which may be expected of the trickling filter.

Verification of First-Order Removal

It has been proposed, although not rigidly shown, that the removal rate in a trickling filter proceeds along the lines of a first-order equation. The equations of Velz, Howland, Schulze, and Eckenfelder all utilize the assumption of first-order removal, but each author proposes without verification that this is so. It was to be a part of this experiment, if possible, to show that the degradation of organic matter within the filter environment followed the assumption of first-order removal. By utilizing the concept of total organics, it is possible to verify that this is so.

The results of the experimental runs are shown graphically in Figure 12. The figure shows the total organics remaining plotted against the depth of the filter on semi-logarithmic paper. It is obvious from the straight-line plot that the removal within the filter does follow a first-order equation and that the family of curves exhibits a similar slope for each individual filter run. Table IV summarizes the data presented in the semi-logarithmic plot. There it may be seen that,

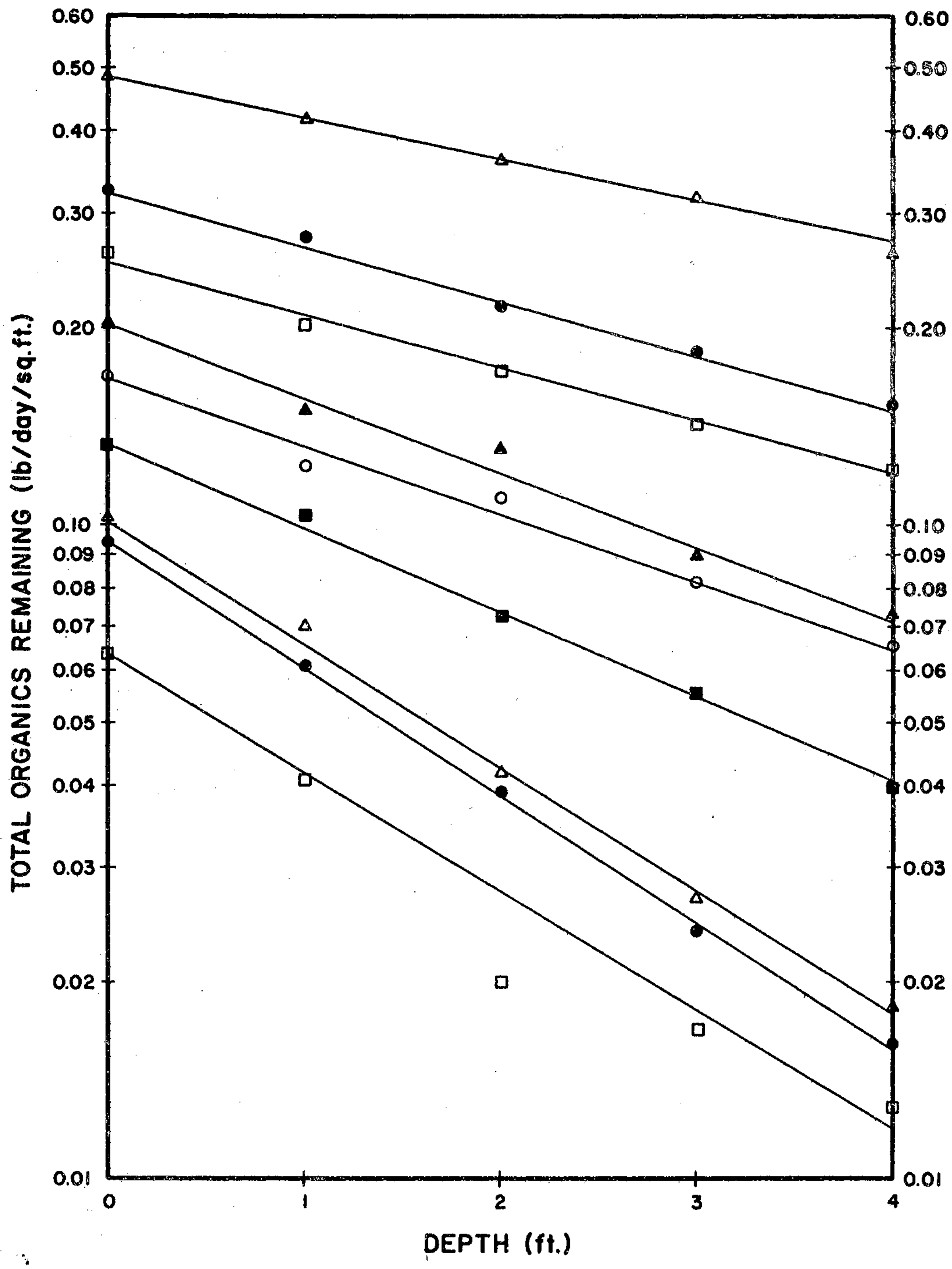

Figure 12. Amount of Total Organics Remaining vs. Depth

TABLE IV

COMPARISON OF THE PERCENT OF APPLIED ORGANICS REMOVED PER FOOT OF DEPTH

Depth (ft)	Description	Initial Total Organics = 0.485 lb/day/ft^2	Initial Total Organics = 0.320 lb/day/ft^2	Initial Total Organics = 0.250 lb/day/ft^2	Initial Total Organics = 0.133 lb/day/ft^2	Initial Total Organics = 0.095 lb/day/ft^2
1	Organics applied (lb/day/ft^2)	0.485	0.320	0.250	0.133	0.095
	Organics removed (lb/day/ft^2)	0.065	0.055	0.040	0.034	0.035
	Percent of applied removed	13.4	17.2	16.0	25.5	36.8
2	Organics applied (lb/day/ft^2)	0.420	0.265	0.210	0.099	0.060
	Organics removed (lb/day/ft^2)	0.060	0.045	0.035	0.026	0.021
	Percent of applied removed	14.3	17.0	16.6	26.3	35.0
3	Organics applied (lb/day/ft^2)	0.360	0.220	0.175	0.073	0.039
	Organics removed (lb/day/ft^2)	0.045	0.040	0.030	0.018	0.014
	Percent of applied removed	12.5	18.2	17.1	24.7	35.9
4	Organics applied (lb/day/ft^2)	0.315	0.180	0.145	0.055	0.025
	Organics removed (lb/day/ft^2)	0.045	0.030	0.025	0.015	0.009
	Percent of applied removed	14.3	16.7	17.2	27.3	36.0

true to the prediction of Velz, at a given total organic loading, each foot of depth of the filter will remove a constant percentage of the organic matter applied to it. Also apparent is the fact that as the initial total organic load applied to the filter decreases, the removal efficiency for each foot of depth of the filter increases. Thus, not only has the assumption of first-order removal been verified, but also Velz' concept of removal with respect to depth.

pH Change with a Change in Loadings

Also a matter of interest in the workings of the trickling filter process is the change of pH as the filter liquor passes through the depth of the filter. Very little has been written on the subject, so it was a secondary objective of this experiment to examine the variation of pH with a change in hydraulic and organic loadings.

Figure 13 is a composite plot of the fluctuation of pH with increasing organic loading as the filter liquor passes through the depth of the filter under conditions of constant hydraulic loading, and Figure 14 is a composite plot of the fluctuation of pH with increasing hydraulic load as it passes through the filter under conditions of constant organic loading. As can be seen, in almost every case the pH drops sharply in the first foot of treatment and then gradually increases, until it practically reaches its original value after the fourth foot. This is particularly true of the lighter organic loadings and the lower hydraulic rates of flow. At heavier organic loadings and higher rates of flow through the filter, the recovery of the pH is less and seldom does it approach its original value.

Figure 15 is a plot of the pH change of a series of equal total

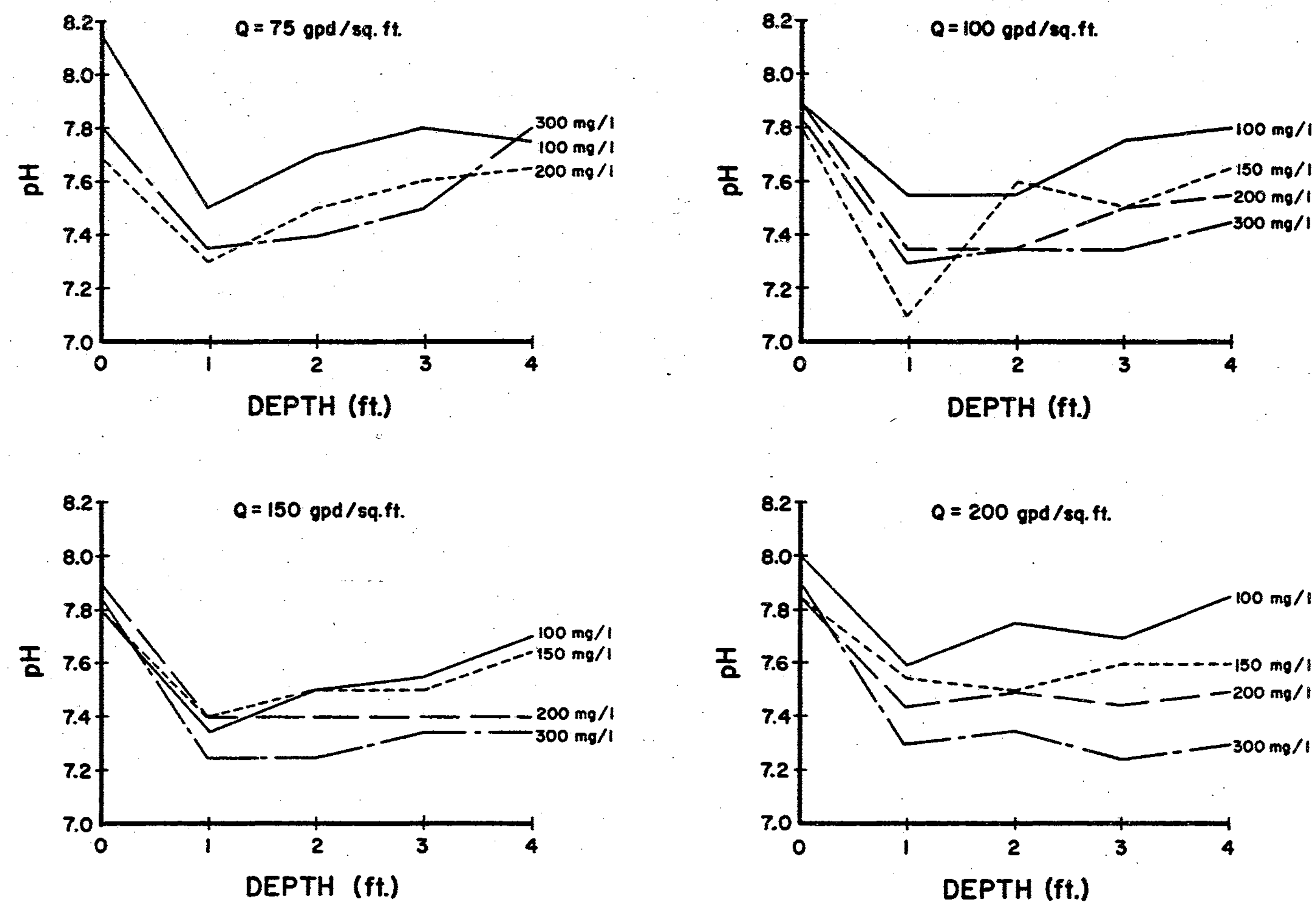

Figure 13. pH vs. Depth Under Conditions of Constant Hydraulic Loadings

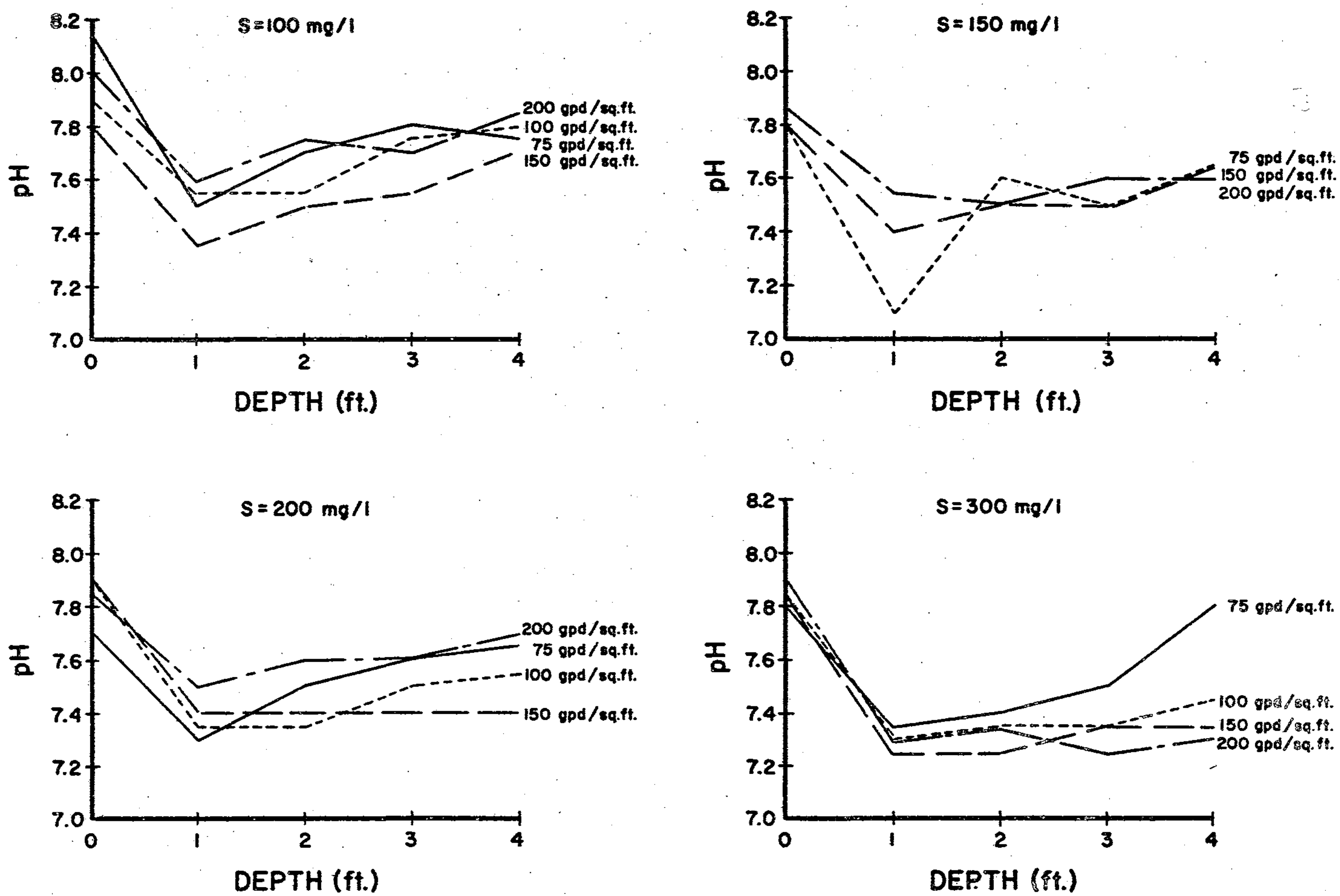

Figure 14. pH vs. Depth Under Conditions of Constant Organic Loadings

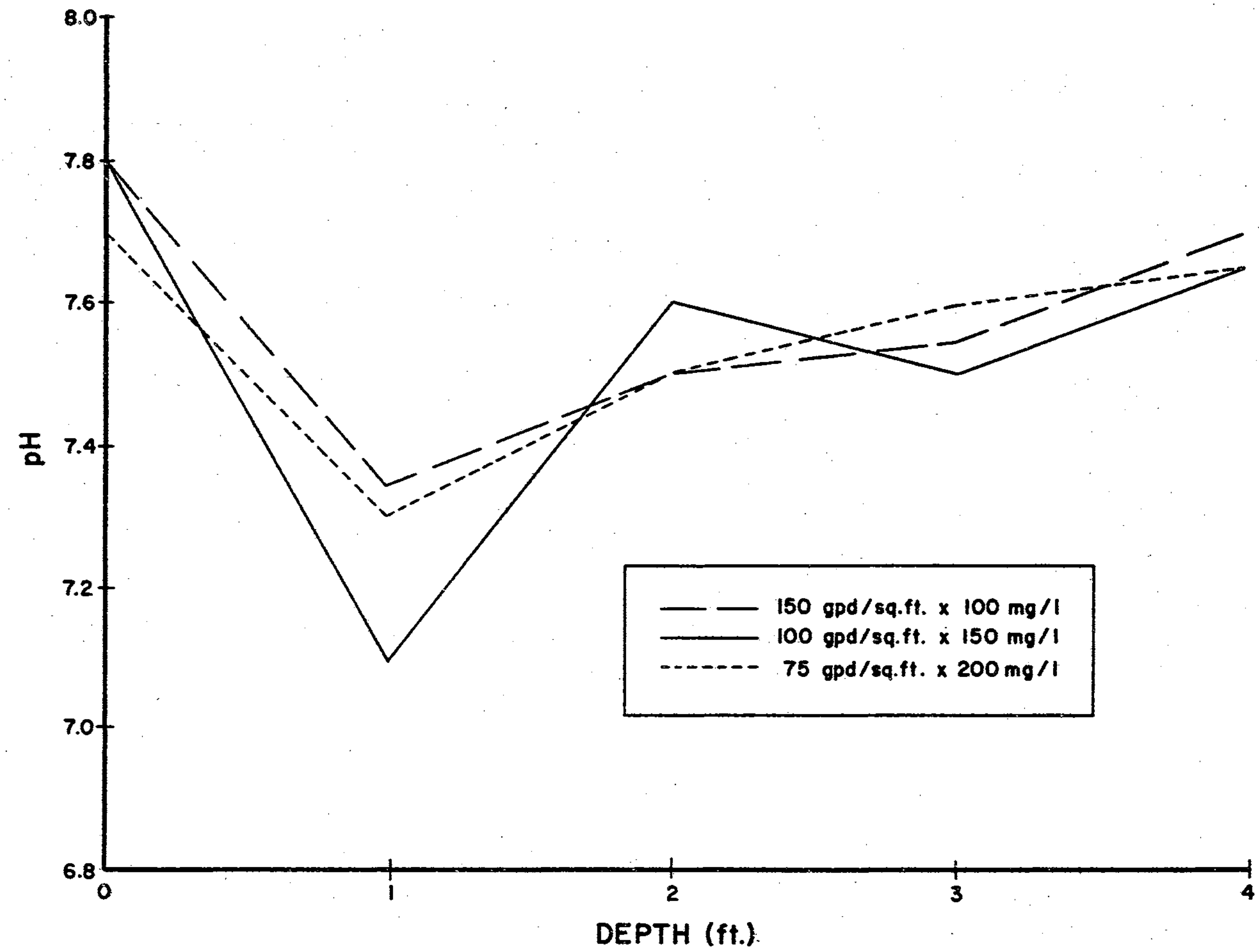

Figure 15. pH versus Depth for Equal Total Organic Loadings

organic runs. It tends to confirm the concept of total organics as a measure of filter performance. As will be noticed, runs with nearly equal total organic loads produce very similar pH changes throughout the depth of the filter, within the limits of this experiment. It would seem that the hydraulic rate of flow would tend to balance out the usage of organic matter as the flow increased, as would be the case when the filter was forced to treat a high concentration waste. In either case, the lower depths of the filter would receive a greater portion of the waste water at higher organic and hydraulic rates of application than at lower ones.

CHAPTER VI

DISCUSSION OF RESULTS

General

This investigation into the effects of the organic loading level and the hydraulic loading rate upon the performance and efficiency of removal of a model trickling filter was carried out under a relatively narrow range of values, corresponding to the loadings to be found in an intermediate-rate trickling filter. It is to be expected, therefore, that the occurrences herein reported will have some correlation with the performance of an actual trickling filter, and in that respect, the experimentation is justified in its existence. These experiments were conducted to determine if either or both of the parameters could be considered independent of the other, and if not, what would be the effects of combining the two into a single factor.

Evaluation of Individual Effects

It is apparent in examining Figures 3 through 6 and Figures 7 through 10 that neither of the two parameters of organic loading level or hydraulic loading rate can be considered independent, for as the organic level was raised under conditions of constant hydraulic loading, the relative percentages of COD remaining in each foot of the filter bed increased, and as the hydraulic rate was raised under conditions of constant organic loading, the same was true. Had either of the parameters been independent, the percentages removed per foot of depth of the filter would have remained fairly constant no matter what the load. Because both exhibited definite effects upon filter performance, it was decided to include both in a single factor based upon the amount of total organics applied to the filter bed per day.

Evaluation of Total Organic Loadings

The parameter of total organic loading affords a much better correlation of data than either consideration of constant organic or constant hydraulic loading. Table II shows that when a filter is judged on the basis of constant hydraulic or constant organic loading, the efficiencies of removal are erratic and tend generally to decrease with increasing hydraulic and organic load. If, on the other hand, one considers the total load applied to the filter per day, it does not matter whether the load is due to a high-concentration sewage at a low flow rate or a low-concentration sewage at a high flow rate because the filter will remove approximately the same percentage of organic matter per foot of depth.

In this experiment, total organics were grouped together according to the nearness of their total organic loads. For example, there were several organic loadings that were exactly equal (200 gpd/ft^2 at 150 mg/l and 100 gpd/ft^2 at 300 mg/l), and there were several that were not equal but which were very close (100 gpd/ft^2 at 100 mg/l and 75 gpd/ft^2 at 150 mg/l). It was felt that the closeness of the total loads would be justification for the equal groupings, but the question arises of just how far apart could two total organic loadings be and still be considered similar. It was found that when the difference in total organic loading exceeded approximately 0.02 lb/day/ft^2, two loading levels exhibited dissimilar reduction properties. For example, the total organic difference between 100 gpd/ft^2 at 100 mg/l and 75 gpd/ft^2 at 150 mg/l equals about 0.01 lb/day/ft^2. These two total organic loadings exhibit similar total organic loadings and removals throughout the depth of the filter. But the total organic difference between 100 gpd/ft^2 at 150 mg/l and 100 gpd/ft^2 at 100 mg/l is just over 0.04 lb/day/ft^2, and it is apparent from examination of Table II that there is enough difference in the treatment properties to cause the formation of a distinctly new total organics level.

It is apparent in the plot of Figure 11 that the trickling filter has a limiting percentage removal. For comparatively light total organic loadings (less than 0.2 lb/day/ft^2) there is a sharp drop in the percent of total organics remaining, and for the comparatively heavier loadings (greater than 0.3 lb/day/ft^2) there is a tendency toward saturation and a constant percentage removal no matter what the load.

Evaluation of First-Order Removal

The concept of total organic loading aids in the presentation of the verification of first-order removal. Figure 12 shows clearly that the removal is definitely first-order because of the straight-line plot on semi-logarithmic paper. It is interesting to note that each of the individual total organic runs has the same slope no matter how wide the difference in total organics applied. This leads to the conclusion that the same percentages will be removed in each foot of the filter at a constant total organic loading, a conclusion which Table IV bears out. Thus, it is shown that the formula of Velz, the constant percentage removal of organics with respect to depth, $dL/dD = -kL$, is borne out.

Evaluation of pH Fluctuation

It is also of interest to note the variation of the pH as the filter liquor passes through the depth of the filter. The technique of sampling at each foot of depth turns out to be a very useful one, as it enables one to plot a pH profile at each foot of depth. It is seen that, within the limitations of this experiment, the pH drawdown is practically all in the first foot of depth and that thereafter the pH tends to rise toward its original nozzle value. Generally speaking, the recovery is greater for light organic loadings and for low hydraulic loadings (and, consequently, for lighter total organic loadings) than for their opposites. As the total organic loadings become heavier, the tendency is for the pH to recover less and less, until, theoretically, at some total organic level the pH is the same in each foot of the filter. The change in pH can be explained as microbial activity. Because there is an abundance of food in the first foot of depth of the filter, there is an abundance of microorganisms to feed. Apparently as the food material is utilized, the pH is forced to drop, the amount of drop being related to the amount of food used. At low total organic levels, the microorganisms are able to assimilate most of the food in the first foot or two feet, and the remaining feet of depth get little nourishment, and, therefore, harbor few microorganisms. But at higher organic rates of loading there is an overabundance of food, and at higher rates of flow the food is washed deeper into the filter, either case of which will tend to drive the food deeper into the bed and force utilization by the microbes dwelling deeper in the filter, thus bringing the pH levels nearer to that encountered in the first foot of depth. It is felt that a further, more extensive examination of the variation of pH with respect to total organic loading may prove to be a useful parameter in the evaluation of trickling filter performance.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Based upon the experimental evidence presented herein, the following conclusions may be drawn concerning the effects of hydraulic loading rate and organic loading level upon the performance and efficiency of trickling filters within the range of this experiment:

1. Neither the organic loading concentration nor the hydraulic loading rate can be considered to be independent in the trickling filter process.

2. Total organic loading provides a better method of filter performance evaluation than does consideration of the organic or the hydraulic loading individually.

3. Equal, or very nearly equal, total organic loadings produce similar removal throughout the depth of the filter.

4. The removal throughout the depth of the trickling filter is first-order and according to the Velz Formula.

5. Each foot of depth of the trickling filter removes a constant percentage of the total organic load applied to it.

6. There is a limiting value of percent removal of COD within the trickling filter.

7. The pH changes sharply through the first foot of depth of the filter and attempts to rise to its original value throughout the rest of the filter depth. The rise is affected by the amount of total organic

loading placed upon the filter.

CHAPTER VIII

SUGGESTIONS FOR FUTURE WORK

As a result of the investigation herein reported, the following suggestions are presented for future study of the relationship of hydraulic and organic loading to the efficiency of the trickling filter process:

1. This study has shown that, within a narrow range of values, there is a better correlation of the parameters to the filter efficiency when the two are combined into a single factor, the total organic loading. Further work with a greater range of comparable total loads, varying each parameter through a wide spectrum of values, could be of considerable importance.

2. In this investigation, the organic loading levels were maintained while the hydraulic loading rates were varied. It would be of some interest to maintain the hydraulic rates while varying the organic levels and then comparing the results with those of this experiment.

3. Investigations into the nature of the pH change within the trickling filter are few, and yet this study shows that there is a definite fluctuation through the depth of the filter. Also, the data show that equal, or very nearly equal, total organic loads produce similar pH profiles. It is suggested that a further and more detailed investigation of the pH change in the bed of a trickling filter would be of benefit.

4. The studies herein reported were carried out in a model trickling filter which utilized once-through treatment only. It would be of some importance to investigate the results when a recirculation factor was introduced.

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