United States Environmental Protection Agency
Municipal Environmental Research Laboratory Cincinnati OH 45268
Research and Development
EPA-600/S2-81-228 Dec. 1981

Project Summary

Performance of Trickling Filter Plants: Reliability, Stability and Variability

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Effluent quality variability from trickling filters was examined in this study by statistically analyzing daily effluent BOD_5 and suspended solids data from 11 treatment plants. Summary statistics (mean, standard deviation, etc.) were examined to determine the general characteristics of those data. Distributions of most effluent data were skewed to the right, and daily suspended solids data generally exhibited more variation than daily BOD_5 data.

Five probability distribution functions, chosen through experience and the literature, were tested to determine which would be best used to describe daily, 7-day average and 30-day average effluent data distributions. Three distributions (the two parameter empirical, the gamma, and the log normal) were found to be adequate, with the log normal being preferred because of ease of application.

Daily effluent BOD_5 and suspended solids data were found to contain both random and nonrandom components. Weekly cycles were found in about half of the plants studied, and significant month-to-month variation in effluent quality was found in every plant. Effluent BOD and suspended solids concentrations were higher in winter than in summer when pooled data from all plants were examined.

Multiple regression analysis was used to determine the effects of various process parameters on effluent quality. In general, primary effluent BOD_5 and suspended solids concentrations and wastewater temperature had the greatest effect. Variation due to measurement error was estimated to be 5 to 78 percent and 11 to 78 percent for effluent BOD_5 and suspended solids values, respectively.

Methods for incorporating statistical concepts into trickling filter design and operation are discussed.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

As discharge requirements have become more stringent, it has become necessary to include concepts of variability into the theory, design, and regulation of wastewater treatment plants. For example, limitations on the average daily and weekly concentrations of pollutants have made it necessary not only to insure that average performance is within discharge limits, but also to reduce the amount of variation in performance.

A number of recent studies have examined effluent variability in wastewater treatment plants, but most of these studies have been concerned solely with activated sludge plant performance. The purpose of this study was to investigate and characterize the nature and sources of variability of effluent quality in trickling filter wastewater treatment plants. Five-day biochemical oxygen demand (BOD_5) and suspended solids (SS) concentrations are the effluent quality parameters that are examined.

Most theoretical and laboratory work on wastewater treatment processes, and practically all studies of data from full scale treatment plants, have been based on deterministic, steady state concepts. Recently, however, dynamic and stochastic models have been developed for both the activated sludge and trickling filter processes. Laboratory studies have been done on the activated sludge process under variable loading conditions, and treatment plant influent and effluent data have been studied using sophisticated stochastic models.

There exists a need to incorporate the concept of variability in virtually every area of the wastewater treatment field. Numerous authors have argued that stochastic concepts should be included in wastewater treatment plant planning, design, and regulation. In the following sections, areas in which consideration of treatment variability is important are discussed.

Variability of Trickling Filter Processes

Discharge Requirements

Effluent variability is implicitly recognized in current federal secondary treatment standards plant discharge limits. The 7-day average maximums allow for the fact that short term fluctuations tend to be averaged out in the long run.

However, daily, weekly and monthly concentration limits are not explicitly stochastic because they set maximum values that cannot be exceeded (without causing a violation). These fixed limits, especially daily maximums, are conceptually inconsistent with the stochastic nature of wastewater treatment processes and requirements should be restated in a probabilistic manner. An example of a probabilistic standard would be one in which the daily composite average BOD_5 concentration cannot exceed a specific value more than two times in any consecutive 30-day period.

Design

Stochastic concepts are also useful in treatment plant design. Designers must consider the degree of variability to be expected, as well as the average performance, if discharge requirements are to be met. Currently, most design techniques are based on steady state assumptions and average constituent values are used for design parameters. One method of accommodating process variability is to oversize the treatment units. Another way to allow for process variability is to determine the expected effluent variation based on data from existing treatment plants. Linear regression models can be developed to predict the distribution percentiles of effluent BOD and SS concentrations, based on the annual mean value of each parameter. Working backwards, designers can choose an effluent concentration not to be exceeded more than a prescribed percentage of the time and then calculate the required average value. Using these computed average values as design criteria, traditional design methods can then be used to size the treatment units. If the design averages are achieved, treatment variability should be within the expected limits.

Possibly a more cost effective approach to reducing the occurrence of high effluent concentrations is to reduce the variability of treatment processes rather than improving the average performance of these processes. Reducing the variability has the effect of narrowing the distributions of effluent values. The use of equalization chambers and automatic process control have been proposed for the purpose of reducing effluent variability. Equalization of influent flows reduces loading fluctuations; because the treatment process is operated under loading conditions that approach steady state conditions, fluctuations in process performance are reduced. Effluent flow equalization before discharge reduces effluent quality variation directly by mixing flows from different periods of process performance. Automatic control can be used to adjust process parameters to compensate for changes in loading conditions and process efficiently.

Fluctuations in Trickling Filter Performance

Effluent quality variability in trickling filter plants is caused by a number of environmental, operational, and loading factors. Factors that cause fluctuations in trickling filter performance are discussed below.

The wastewater flow rate through the trickling filter controls the thickness and velocity of the liquid film on the biological slime. An increase in flow rate increases the film thickness, which in turn inhibits oxygen transfer through the film. Higher liquid velocities reduce the contact time for diffusion of organics from the liquid into the slime. Thus the overall effect of increased flowrate is a higher filter effluent BOD concentration for a given influent BOD concentration.

An increase in the concentration of organic matter entering the filter generally causes an increase in the filter effluent organic concentration. Increased organic concentration increases the mass loading rate on the filter and raises the concentration of organics in the liquid film. The increased concentration of organics causes food and nutrients to penetrate deeper into the slime layer, which increases the reaction rate per unit area unless the maximum reaction rate has been reached or some other factor, such as oxygen transfer, has become rate limiting. Although the mass removal rate increases, it does not increase as much as the increase in mass loading, and the net result is a higher filter effluent organic BOD concentration.

Air and wastewater temperature both affect treatment efficiency. A temperature increase in the liquid film and biological slime increases transport and reaction rates, thus improving treatment efficiency. In conventional filters, the supply of air (and thus oxygen) to the microorganisms is controlled by the relationship between air and wastewater temperature. The greater the difference between air and water temperature, the greater the draft through the filter.

Other factors that affect filter operation are wastewater pH and the presence of toxic substances. The optimal pH for microbial growth in conventional biological treatment is between 6.5 and 8.5. If the pH is considerably outside this range, treatment efficiency will decrease. Toxic substances in the influent can also retard biological activity and reduce treatment efficiency.

Trickling filters are quasi-natural biological processes, and there is evidence that slime growth-decay cycles occur locally within the filter, independent of fluctuations in flow rate, organic concentration or other parameters. It is not known whether these cycles cause significant variations in the overall performance of the filter.

Fluctuations in Clarifier Performance

The most important factors that affect clarifier performance are the concentration and composition of incoming suspended matter and the flow rate through the tank. An increase in flow rate decreases the time available for particles to settle to the bottom of the tank and thus increases the concentration of particles in the clarifier effluent.

Density, shape, and size all affect the settling velocity of particles. An increase in the settling velocity of the suspended particles entering the clarifier results in an increase in the percentage of particles removed.

Higher concentrations of suspended matter in the clarifier influent generally result in higher effluent concentrations because there is an increase in the concentration of particles with settling velocities too low to be removed.

Flocculation and straining of particles also affect suspended solids removal in clarifiers, but these mechanisms cannot be explained simply in terms of clarifier influent strength and flow rate.

Other factors can influence clarifier performance. Improperly operated sludge scrapers can cause disruptive currents in the tank, and settled solids that remain on the bottom of the tank too long can become anaerobic and produce gas bubbles that float solids to the water surface.

Objectives

The purpose of this study is to investigate the characteristics and some possible sources of variability in final effluent quality in trickling filter wastewater treatment plants. Daily performance data have been obtained from 11 treatment plants and analyzed statistically to investigate the following questions:

1. How can the distributions of effluent BOD_5 and SS concentrations from trickling filter plants be characterized?
2. Are trickling filter effluent BOD_5 and SS concentrations data random?
3. If trickling filter plant effluent BOD_5 and SS data are not random, do the data follow any annual or weekly cycles?
4. What are the effects of influent, environmental, and operational parameters on effluent variability?
5. What is the effect of measurement error on effluent data variability?

It would be worthwhile to study the variability of each process. However, data from between the trickling filter and final clarifier are not generally available. Therefore, in this study only the variability of the final effluent is examined.

Procedures

The data base for this study consists of daily operation and performance records from 11 trickling filter plants (Table 1) located in six different states. Data sets from most of the plants are 1 year in length, but the data from plants 5 and 7 are somewhat longer. All concentration data are flow weighted composite values.

Characterization of Effluent Distributions

To characterize the effluent BOD_5 and SS distributions for the treatment plants in this study, summary statistics such as the mean, standard deviation, and skew coefficient were computed for daily, 7-day average and 30-day average effluent concentrations from each plant. Also, three theoretical and two empirical distribution functions were chosen as possible models for effluent distributions and were tested using the Kolmogorov-Smirnov goodness-of-fit test. Details of these procedures are explained below.

Running Averages

Portions of federal and state discharge requirements for BOD_5 and SS concentrations are stated in terms of running 7- and 30-day averages. Therefore, the distributions of these averages, as well as the distributions of daily averages, are of interest and will be investigated in this study. Trickling filter effluent data are not random, and it cannot be assumed that running average distributions are approximately normal. Therefore, the distributions of

Table 1. Trickling Filter Treatment Plants Studied

Plant Number	*Location*	*Period of Data*	*Type of Process*	*Average Flow (mgd)*
1	*Iowa*	*Jan '76 - Dec '76*	*2-stage*	*33.7*
2	*Michigan*	*Jan '76 - Dec '76*	*1-stage*	*0.5*
3	*Wisconsin*	*Jan '76 - Dec '76*	*2-stage*	*7.6*
4	*Michigan*	*Jan '76 - Dec '76*	*1-stage*	*0.8*
5	*Ohio*	*Feb '76 - July '77*	*1-stage*	*15.8*
6	*Michigan*	*Jan '77 - Dec '77*	*2-stage*	*0.9*
7	*Michigan*	*Jan '76 - Jan '77*	*1-stage*	*11.6*
8	*Oklahoma*	*Jan '76 - Dec '76*	*2-stage*	*12.3*
9	*Michigan*	*Sept '76 - Aug '77*	*1-stage*	*4.0*
10	*Michigan*	*Dec '76 - Nov '77*	*1-stage*	*0.8*
11	*Arkansas*	*Jan '77 - Dec '77*	*2-stage*	*6.0*

running averages had to be determined in the same manner as the distributions of daily averages.

Summary Statistics

The following summary statistics have been computed for daily, 7-day average, and 30-day average effluent BOD_5 and SS concentration data from each plant:

arithmetic mean
standard deviation
coefficient of variation
skew coefficient
maximum observation
minimum observation
number of valid observations

Examination of these statistics will provide information on the central tendencies, ranges and shapes of the effluent BOD_5 and SS concentration distributions for data from each plant.

Theoretical Distribution Models

Virtually an unlimited number of theoretical distribution functions could be tested for fit with the effluent data. Practical limitations prevent testing more than a few. The normal, log-normal, and gamma distributions are good candidates because of their simplicity, widespread use, and demonstrated usefulness in previous studies of wastewater treatment process performance.

Empirical Distribution Models

Strong linear relationships between annual mean and percentile concentration values have been shown to exist in previous studies. For example, if one year's effluent BOD_5 data for a group of plants is placed in ascending order, the 95th percentile value will be approximately proportional to the plant's annual mean value.

The set of linear regression equations developed for the percentile values do not, by themselves, define a continuous probability distribution. However, given the mean value from a set of data, a finite number of predicted percentile values can be determined. A continuous distribution can then be constructed by linearly interpolating between each of the predicted percentile values.

Kolmogorov-Smirnov Goodness-of-Fit Test

The usefulness of each of the five (proposed) distribution functions for modeling BOD_5 and SS data from each plant was examined using the Kolmogorov-Smirnov goodness-of-fit test. The null hypothesis for this test is:

> "The observed data were sampled from an underlying population which is distributed according to the hypothesized distribution function."

It is assumed that if the test hypothesis is true, any differences between the observed distribution and the hypothesized distribution are due to the effects of random sampling.

Randomness of Effluent Data

It was important to determine if trickling filter effluent BOD_5 and SS concentration data were random. If the trickling filter effluent data are not random, then distribution models for effluent data are not random, and distribution models for effluent concentrations cannot be used in the classical manner because probability density functions are usually assumed to be based on random data. Another consequence of nonrandomness would be that predictable cycles might exist in effluent data.

The randomness of trickling filter effluent BOD_5 and SS concentration data have been tested using the runs test and a test for serial correlation. In addition to simply determining if the data are random, these tests can be used to determine the relative magnitude of nonrandomness in each set of data and to provide a basis for comparing the relative randomness of different sets of data.

The runs test is a general purpose test of the randomness of a data series. Trend, grouping, and many types of cyclical movement in the data can be detected. In some cases, the runs test fails to detect dependence between successive values of a data series. It is therefore prudent to perform a test for correlation between consecutive data pairs (serial correlation) in addition to the runs test when examining data randomness.

The test for serial correlation is performed by treating the original data series as one variable, x_t, and treating the data series shifted forward one observation as the other variable, x_{t-1}. The Pearson correlation coefficient, a measure of association of the strength of the linear relationship between two variables, is then computed to test for correlation between x_t and x_{t-1}. If the data are random, the correlation coefficient will tend towards zero.

Annual and Weekly Cycles

To the test for the possibility of weekly or annual cycles in trickling filter effluent data, a two-way analysis of variance was performed on effluent BOD_5 and SS concentration data from each plant. Analysis of variance was not used to explicitly determine if cycles existed in the data series, but merely to determine if effluent concentrations were dependent on the month or day of the week on which they occurred. However, if effluent BOD_5 (or SS) concentrations from a treatment plant were found to be dependent on the day of the week, it was concluded that a weekly cycle existed in that data set.

A similar conclusion concerning annual cycles could not be made for data that were found to be dependent on the month. With only 1 year of data from each plant, there was no way of determining if an observed annual sequence was representative of a repeating annual cycle or merely part of a random fluctuation in average monthly performance. All that could be concluded in this case was that some variation in the data was due to significant changes in average performance from month to month.

Effects of Various Process Parameters

The effects of influent, environmental, and operational parameters on effluent variability were examined by using multiple linear regression analysis. This analysis studied the correlations between various process parameters and effluent BOD_5 and SS concentrations.

The regression analysis has been conducted in two parts. First, multiple linear regression equations predicting effluent BOD_5 and SS concentrations for each plant were constructed using linear combinations of the following independent variables:

flow, Q
influent BOD_5 and SS concentrations, BOD_i, SS_i

primary effluent BOD_5 and SS concentrations, BOD_p, SS_p
the inverse of the average influent water temperature, $WTEMP^{-1}$
the inverse of the average air temperature, $ATEMP^{-1}$
the deviation from 7.0 of the influent pH, 7.0-pH
recycle ratio, R

Second, to test the relation importance of quadratic terms, loading factors, combinations of terms and values of parameters from previous days (lagged variables), regression equations using the terms above as well as the following terms were constructed:

quadratic terms: BOD_i^2, SS_i^2, BOD_p^2, SS_p^2

loading factors: $Q{\cdot}BOD_i$, $Q{\cdot}SS_i$, $Q{\cdot}BOD_p$, $Q{\cdot}SS_p$

combinations of terms: $T_{avg} = (ATEMP + WTEMP)/2$, $T_d = |ATEMP-WTEMP|$

lagged terms: $BOD_{i,t-1}$, $SS_{i,t-1}$, $BOD_{p,t-1}$, $SS_{p,t-1}$, $BOD_{i,t-2}$, $SS_{i,t-2}$, $BOD_{p,t-2}$, $SS_{p,t-2}$, $ATEMP_{t-1}$

Measurement Error

Any discussion of the causes of variation in a series of measured quantities should include consideration of the effect of measurement error. Like all laboratory procedures, the BOD_5 and SS tests have a finite degree of precision. Thus even if the effluent from a treatment plant was of perfectly uniform quality at all times, and in addition, the effluent was always sampled without error, the measured BOD_5 and SS concentrations would still vary from sample to sample because of the inherent variability in the methods of analysis.

It is possible to determine how much variation in trickling filter effluent data is caused by measurement errors because the variation due to the limited precision of the BOD_5 and SS tests is independent of other sources of variation in the data.

A simplifying assumption has been made to estimate the variation due to measurement error. Because the precision of the BOD_5 and SS tests is a function of the concentrations being measured, the precision of these tests varies from day to day. For simplicity, it will be assumed that the fractional standard deviations of the measurement errors are a function of each plant's annual mean effluent BOD_5 and SS concentrations.

Results

The characterization of daily, running 7-day average and running 30-day average effluent BOD_5 and SS concentration data was conducted in three steps. First, summary statistics for each type of effluent data set were computed for each treatment plant (Tables 2, 3, and 4). Second, coefficients for two empirical distribution models were computed. Third, two empirical and three theoretical distribution models were tested to determine their usefulness in modeling effluent data from each plant.

Some general characteristics of trickling filter effluent data can be seen from these results. For the daily data, the averages of the mean BOD_5 from all plants and the mean SS concentration from all plants are approximately equal. However, the average standard deviation for SS data is somewhat higher than the average standard deviation for BOD_5 data. Thus it may be concluded that, overall, BOD_5 and SS data tend to be of the same average magnitude but that SS data tend to be somewhat more variable.

Comparison of Distribution Models

Five probability distributions have been tested for their fit to effluent BOD_5 and SS data using the Kolmogorov-Smirnov (K-S) goodness-of-fit test. Distributions tested were the one- and two-parameter empirical models and the normal, log-normal, and gamma distribution functions.

For any single effluent parameter (e.g., daily BOD_5, 7-day average SS, etc.) the distribution that best fit the data changed from treatment plant to treatment plant. However, it can be concluded that, in general, the log-normal, gamma, and two-parameter empirical distribution functions are equivalent for the purpose of describing effluent data distributions.

Randomness of Effluent Data

Using a 5-percent significance level as the rejection criterion, the hypothesis of randomness can be rejected for every set of BOD and SS data on the basis of at least one of the two tests. It can be concluded that the BOD data from every plant and the SS data from every plant but one are highly nonrandom. For 9 out of the 11 treatment plants, it can be concluded that, for most of the treatment plants studied, effluent BOD_5 data are less random than SS data.

Annual and Weekly Cycles

It may be concluded from the results of the randomness tests that there are significant nonrandom patterns in trickling filter effluent data. The existence of annual or weekly cycles in the data has been examined by performing a two-way analysis of variance on BOD_5 and SS data from each plant and by pooling normalized data from all the treatment plants and plotting the averages for each month and day of the week.

For each treatment plant studied, effluent BOD_5 and SS concentrations are in some manner dependent on the month in which they occur. The ratios of maximum monthly average to minimum monthly average and the differences between monthly averages are of physical as well as of statistical significance. Because only 1 year of data from each plant was used, it may not be concluded that effluent concentrations at these 11 treatment plants have repeating annual cycles.

The effluent concentrations in eight sets of data depend on the day of the week on which they occur. Because there are 52 weeks in each set of data, it may be concluded that there is a repeating weekly cycle in each of these eight data sets. Existence of any general weekly or annual patterns in the effluent data from all the treatment plants was studied by plotting monthly and daily averages for pooled data. Effluent BOD_5 and SS concentration data from each treatment plant were first normalized. Normalized data from all of the treatment plants were pooled together and grouped according to the month in which the data were taken. To study weekly patterns, effluent data from the nine treatment plants with daily data were pooled and then grouped according to the day of the week on which the data occurred. Effluent BOD_5 and SS data tend to have annual cycles that are roughly in phase with one another. Concentrations of both BOD_5 and SS tend to be higher than average in the winter months and lower than average in the summer and early fall.

Table 2. Summary Statistics for Daily Effluent BOD_5 and Suspended Solids Concentrations

	BOD_5							Suspended Solids						
Plant Number	Mean (g/m³)	Sx (g/m³)	V_x	Skew	Max (g/m³)	Min (g/m³)	Valid Obs	Mean (g/m³)	Sx (g/m³)	V_x	Skew	Max (g/m³)	Min (g/m³)	Valid Obs
1	33.31	15.28	0.46	0.92	102.0	8.0	357	52.50	31.17	0.59	2.26	280.0	6.0	356
2	10.73	7.24	0.67	1.62	43.0	0.0	365	21.45	13.35	0.62	1.15	80.0	1.0	366
3	10.05	7.52	0.75	1.68	61.0	1.0	362	21.04	16.69	0.79	1.17	88.0	1.0	361
4	58.35	20.83	0.36	0.10	107.0	22.0	250	54.85	15.02	0.27	0.10	94.0	20.0	250
5	29.24	11.21	0.38	1.31	93.0	6.0	492	18.34	8.81	0.48	2.16	84.0	3.0	493
6	27.04	6.75	0.25	0.09	58.0	3.0	365	15.09	5.98	0.40	0.40	37.0	2.0	365
7	23.21	16.93	0.73	1.62	100.0	1.0	383	24.05	15.09	0.63	0.99	86.0	2.0	386
8	43.09	6.59	0.15	0.61	69.0	28.0	365	34.03	13.63	0.40	4.56	172.0	12.0	365
9	51.13	19.95	0.39	0.23	125.0	12.0	359	41.08	17.61	0.43	1.60	130.0	12.0	365
10	21.02	6.22	0.30	-0.15	33.0	8.0	250	23.60	14.42	0.61	1.08	86.0	2.0	250
11	18.31	11.98	0.65	2.17	104.0	0.0	355	16.15	8.85	0.55	1.09	64.0	1.0	363
Average	29.59	11.86	0.46	0.93	--	--	--	29.29	14.60	0.52	1.51	--	--	--
Median	--	11.21	0.39	0.92	93.0	6.0	--	--	14.42	0.55	1.15	86.0	2.0	--

Effects of Process Parameters

Correlations between influent, operational, and environmental process parameters and effluent BOD and SS concentrations were studied using multiple linear regression analysis. Regression equations using combinations of various process parameters as independent variables were constructed in a stepwise manner. All data used in constructing the regression equations were normalized so that the regression coefficients would be easier to interpret.

The regression analysis was conducted in two parts. First, regression equations were developed using simple linear combinations of untransformed variables. In the second part, various transformations and combinations of the independent variables used in the first part were included in the regression analysis. In both steps, only those independent parameters that contributed materially to the significance of the regression equation were included in the final form of the equation.

It was concluded that primary effluent BOD_5 concentration is, in general, highly correlated with effluent BOD_5 concentration. Flow rate, influent BOD_5 concentration, and the reciprocal of influent wastewater temperature are also highly correlated with the effluent BOD_5 for most plants where data were available. Results for the other independent parameters are inconclusive, because there was little correlation, the correlation varied from plant to plant, or because data for that variable were not available from most plants. The regression equations for effluent SS generally have somewhat lower coefficients of determination, indicating that effluent SS concentrations are not correlated to other process parameters as highly as are effluent BOD_5 concentrations.

Variation Caused by Measurement Error

The estimates of variation caused by measurement error are given in Table 5 for effluent concentration data from 11 trickling filter plants. Variation caused by the SS test is greater than for the BOD_5 test for every plant. The standard deviation of the analytical tests is estimated to be between 1.8 and 7.5 g/m³ for BOD_5 and between 5.3 and 10.7

Table 3. Summary Statistics for Continuous 7-Day Averages Effluent BOD and Suspended Solids Concentrations

	BOD_5							Suspended Solids						
Plant Number	Mean (g/m^3)	Sx (g/m^3)	V_x	Skew	Max (g/m^3)	Min (g/m^3)	Valid Obs	Mean (g/m^3)	Sx (g/m^3)	V_x	Skew	Max (g/m^3)	Min (g/m^3)	Valid Obs
1	33.12	11.52	0.35	0.15	62.3	14.0	360	52.52	18.63	0.35	0.38	103.6	17.6	360
2	10.56	4.95	0.47	0.93	25.4	3.1	360	21.22	9.18	0.43	0.70	49.1	6.1	360
3	9.99	4.76	0.48	0.67	24.6	1.7	360	21.14	8.00	0.38	0.26	41.5	5.1	360
4	58.31	20.17	0.35	0.07	96.8	27.2	360	54.82	12.65	0.23	-0.03	78.8	30.0	360
5	29.15	6.86	0.24	0.57	53.1	14.0	514	18.41	5.26	0.29	0.73	39.0	7.3	516
6	27.02	3.86	0.14	-0.39	35.7	14.4	359	15.07	4.40	0.29	0.04	27.4	6.4	359
7	22.87	13.32	0.58	1.48	81.7	7.1	391	23.62	9.84	0.42	0.59	52.3	5.9	391
8	43.00	4.79	0.11	0.45	54.3	34.1	360	34.04	7.17	0.21	1.61	63.1	24.1	360
9	51.49	17.47	0.34	-0.07	82.9	18.3	359	41.23	12.57	0.30	0.73	80.3	18.3	359
10	21.01	4.59	0.22	0.21	29.6	10.0	359	23.86	9.59	0.40	1.21	59.2	6.4	359
11	17.99	8.40	0.47	1.28	48.7	4.5	358	16.11	5.07	0.30	0.60	34.7	5.9	359
Average	--	9.15	0.34	0.49	--	--	--	--	9.31	0.33	0.62	--	--	--
Median	--	6.86	0.35	0.45	53.1	14.0	--	--	9.18	0.31	0.60	52.3	6.4	--

g/m^3 for SS. Although these results are only approximate, it is apparent that a significant percentage of the variation in effluent concentration data is due to the limited precision of the BOD_5 and SS tests.

Discussion

For any given parameter, the distribution that was best for describing effluent data was generally different for each treatment plant. Three distributions (the two-parameter empirical, log-normal, and gamma) were generally comparable and could be used to describe effluent data better than the other two distributions tested. These three distributions can be used to model effluent distributions adequately, but no single distribution, empirical or theoretical, is generally best for modeling effluent distribution from all trickling filter plants. The general characteristics of trickling filter effluent concentration distributions found in this study are in agreement with the results of previous studies on trickling filter and activated sludge plants.

All of the distributions but the one-parameter model fit trickling filter effluent data with roughly the same degree of accuracy. Therefore, the choice of distribution to use in any particular application can be made on the basis of the relative ease with which the different distributions are calculated. Even the one-parameter model can be used to obtain a reasonable, rough estimate of effluent distributions and may be preferable in some applications.

The advantage of using the one-parameter empirical model is that the distribution standard deviation does not have to be calculated or estimated. When the standard deviation must be estimated, the one-parameter model is as accurate for predicting effluent distributions as any of the two-parameter models, unless an unusually good estimate of the standard deviation is available.

Percentiles can be calculated easily for any of the five distributions once the parameters of the distribution are specified. The arithmetic mean and (when required) the standard deviation are sufficient to specify any of the distributions except the log-normal. To use the log-normal distribution, the mean and standard deviation of the logarithms of the data are required, and these are not the same as the logarithms of the arithmetic mean and standard deviation.

If a desired percentile value is specified and (when required) the standard deviation is estimated, any of the five distributions can be used to compute the implied mean value of the distribution. If the gamma distribution is used, an iterative procedure (which is time-consuming unless performed on a computer) must be used to calculate the distribution mean.

Another disadvantage of using the gamma distribution is that only relatively incomplete tables of gamma distribution values are available, and gamma percentiles are difficult to compute. In contrast, complete tables of the normal distribution are available. With some simple conversions, normal tables can be used for the log-normal distribution as well. Of course, tables

Table 4. Summary Statistics for Running 30-Day Average Effluent BOD and Suspended Solids Concentrations

	BOD$_5$							Suspended Solids						
Plant Number	Mean (g/m^3)	Sx (g/m^3)	V_x	Skew	Max (g/m^3)	Min (g/m^3)	Valid Obs	Mean (g/m^3)	Sx (g/m^3)	V_x	Skew	Max (g/m^3)	Min (g/m^3)	Valid Obs
1	32.11	9.91	0.31	0.15	51.9	17.0	337	51.59	15.63	0.30	0.78	88.9	29.7	337
2	10.00	3.53	0.35	1.04	20.7	5.4	337	20.93	7.66	0.37	0.93	41.1	9.5	337
3	9.77	3.69	0.38	0.77	19.6	4.2	337	21.05	5.47	0.26	0.09	31.5	11.0	337
4	57.69	19.85	0.34	0.11	88.9	32.0	337	54.30	11.54	0.21	-0.02	72.2	37.3	337
5	29.03	5.16	0.18	0.57	42.7	20.0	516	18.58	3.81	0.21	0.27	30.5	11.2	516
6	26.78	2.39	0.09	-0.74	31.0	20.2	336	14.85	3.88	0.26	-0.05	21.1	7.47	336
7	22.59	11.63	0.51	1.09	52.1	10.1	368	23.22	7.55	0.33	0.16	38.6	11.2	368
8	42.75	3.98	0.09	0.57	51.7	36.8	337	34.01	4.50	0.13	-0.07	43.1	26.0	337
9	52.94	15.56	0.29	-0.16	79.0	25.1	336	41.81	9.79	0.23	0.40	61.7	26.8	336
10	21.10	3.48	0.16	0.66	27.9	15.7	336	23.99	6.25	0.26	0.23	39.4	11.3	336
11	17.05	6.18	0.36	0.84	34.5	7.8	336	15.81	3.44	0.22	-0.06	24.9	7.9	336
Average	--	7.76	0.28	0.45	--	--	--	--	7.23	0.25	0.24	--	--	--
Median	--	5.16	0.31	0.57	42.7	17.0	--	--	6.25	0.26	0.16	39.4	11.2	--

are not available for the two empirical distribution models, but the calculations involved in using these distributions are simple.

Effluent Standards

The distributions of effluent concentrations must be known if reasonable and consistent effluent standards are to be set. A reasonable standard does not require a level of treatment that cannot be achieved with available technology. Two standards are consistent if neither standard requires a significantly higher level of treatment than the other.

Of the 11 treatment plants in this study, two had a mean effluent BOD$_5$ concentration equal to or less than 17.5 g/m^3 and three had a mean effluent SS concentration equal to or less than 18.6 g/m^3. U.S. Environmental Protection Agency (EPA) secondary standards were attained by a relative minority of trickling filter plants evaluated in this study.

The implied mean effluent BOD$_5$ concentration for the 7-day average standard is 4.8 g/m^3 higher than the implied mean for the 30-day standard. For effluent SS concentrations, the implied mean for the 7-day standard is 2.5 g/m^3 higher than for the 30-day standard. From these results, the conclusion may be made that the 30-day effluent BOD$_5$ standard is significantly more restrictive than the 7-day standard, and that the 30-day effluent SS standard is somewhat more restrictive than the 7-day SS standard. EPA secondary standards are therefore not consistent when applied to trickling filter treatment plants.

Randomness of Effluent Data

Effluent concentration data in this study are not randomly generated and are thus not independent of time and preceding effluent concentrations. The probability that an effluent BOD$_5$ (or SS) concentration will be exceeded on any one day is dependent on which particular day is of interest. Information concerning the conditions under which events occur is not included in distribution functions, and hence no statement concerning the probable level of effluent concentrations on any one day can be made based simply on the distribution models considered in this study.

Distribution models for effluent concentrations do provide information on the long-term behavior of trickling filter performance and can be used to estimate the probable frequency of occurrence of some range of effluent values over a 1-year period.

Annual and Weekly Patterns

On the basis of the analysis of variance results and the plots of pooled, normalized data, the following conclusions can be made concerning effluent BOD$_5$ and SS concentrations at the 11 treatment plants studied.

1. There are significant month-to-month fluctuations in average effluent concentrations for every treatment plant studied.

2. One cause of these monthly fluctuations is an annual cycle in effluent concentrations that is evident when data from all 11 treatment plants is pooled. Effluent concentrations tend to be above average in the winter and below average in the summer.

3. A significant weekly cycle exists in effluent concentration data from some of the treatment plants studied.

4. When data from nine treatment plants were pooled, weekly cycles were evident for BOD_5 and SS data, but the amplitudes of these cycles were less than half the amplitudes of the annual cycles. Effluent BOD and SS concentrations tend to be below average on Sundays, and SS concentrations tend to be above average on Wednesdays.

Table 5. *Variation Caused by Measurement Error*

	Effluent BOD_5		*Effluent Suspended Solids*	
Plant Number	*Estimated Percent of Variation Caused by Measurement Error*	*Standard Deviation (g/m^3)*	*Estimated Percent of Variation Caused by Measurement Error*	*Standard Deviation (g/m^3)*
1	10	4.7	11	10.5
2	7	1.9	23	6.4
3	6	1.8	14	6.3
4	13	7.5	51	10.7
5	15	4.4	44	5.9
6	36	4.0	78	5.3
7	5	3.6	21	6.8
8	78	5.8	37	8.2
9	12	6.9	27	9.1
10	28	3.3	15	5.5
11	6	3.0	37	5.4

Effects of Process Variables on Effluent Concentrations

Based on the results of the multiple regression analyses, it can be concluded that influent, operational, and environmental process variables are correlated with effluent BOD_5 and SS concentration data at trickling filter plants. It has not been proven that fluctuations in effluent data are caused by changes in the independent parameters because regression analysis alone cannot be used to prove cause and effect relationships. Correlations between two variables conceivably could be caused by a third, unmeasured variable. However, the relationships found are consistent with current theoretical models of clarifiers and trickling filters and provide strong evidence to support the hypothesis that a significant percentage of effluent variation in trickling filter plants is caused by fluctuations in process loading and temperature.

Variation Due to Measurement Error

Measurement errors can cause a significant percentage of the total variation in effluent concentrations, especially for SS data. The percentage of the variation in effluent data caused by analytical error was estimated to be greater than 10 percent for BOD_5 and SS concentrations from 7 and 11 plants, respectively, and was greater than 20 percent for BOD_5 and SS data from 3 and 8 plants, respectively.

General Comments

The greater variability and randomness found in SS effluent data may, in part, be due to the fact that measurement errors appear to be somewhat greater for SS than for BOD_5. However, one reason that measurement errors were estimated to be greater for SS data was because of the assumption that duplicate BOD_5 samples were analyzed, but only one SS sample was used. If this assumption is not correct, the estimated measurement errors for SS analysis would be smaller, though they would still be somewhat larger than the estimated errors for BOD_5 data.

The sum of the percentages of variance explained by the regression models and by measurement error is greater than 40 percent for all but three sets of data. From these results, it can be concluded that a large fraction of effluent variability is caused by variation in process parameters and by measurement error. Because three of the sums are greater than 100 percent, the estimates of measurement error are in some cases too high.

Measurement errors do not affect the values of running average data as much as they affect daily data, because the errors tend to cancel out. For example, if the standard deviation of a test is 5.0 g/m^3, the standard deviations of 7-day and 30-day averages for the same parameter would be 1.9 and 0.9 g/m^3, respectively.

Based on the results of this study, it may be concluded that the magnitude of variation in effluent data caused by measurement errors is quite large at many treatment plants. If a treatment plant is operating near its discharge limits, apparent violations of the daily and 7-day average concentration limits can be caused by analytical error alone.

To reduce the possibility of discharge violations caused by measurement error, more replicates of each sample can be analyzed. Also, sampling and laboratory techniques should be checked to see that all sources of sampling and analytical errors are minimized.

Reliability of Trickling Filter Process

The uncertainties associated with plant design and operation should be recognized in the design of trickling filters. The best way to accomplish this is to incorporate stochastic concepts and procedures in the design process. To produce an effluent of high quality and to meet the effluent discharge requirements at minimum cost, design engineers must be able to estimate the average effluent quality and its variations for a given treatment process. Uncertainties and their significance on process performance can be analyzed systematically using methods of probability. A probabilistic approach for design can be used to provide a consistent basis for the analysis of uncertainty and a theoretical basis for the analysis of performance and reliability.

Reliability measures are expressed in probability terms and are defined as the probability of adequate performance (i.e., the percent of the time that effluent concentrations meet requirements). A stochastic model and design tables and graphs have been developed in a related study predicting achievable effluent BOD_5 and SS concentrations based on a proposed coefficient of reliability (COR).* The COR relates mean constituent values to the standard and is achieved on a probability basis and the log-normal distribution assumption. The COR was defined mathematically as:

$$COR = (V_x^2 + 1)^{1/2} \exp\{-Z_{1-\alpha}[\ln(V_x^2 + 1)]^{1/2}\}$$

The coefficient of variation (V_x) for effluent concentration should be estimated from past experience and on reasonable expectation of performance. Values of the coefficient of variation (V_x) from other similar treatment plants may be used as a guidance. Based on cursory examination, coefficient of variations of 0.50 for BOD_5 and 0.55 for SS concentration would appear to be suitable values, however. Reliability as a function of V_x and COR is shown in Figure 1.

To support the validity of the reliability model in prediction of performance of trickling filters, the percent of the time that effluent concentration exceeded 30 g/m^3 was computed for 1 year of data in all 11 plants (Table 18 in the full report). This percent of exceedance was also predicted using the reliability model based on the log-normal assumption. The prediction values are very comparable with the measured values.

To determine the validity of the theoretical results of the COR, Figure 1 was reconstructed based on the 1 year of operational data of all 11 plants. Percentile values of exceedance for effluent BOD_5 and SS from one year of daily operational data have been computed to present an empirical distribution of effluent concentration without considering whether it follows any classical distribution function. The results of COR based on pooled plant data were highly comparable to the

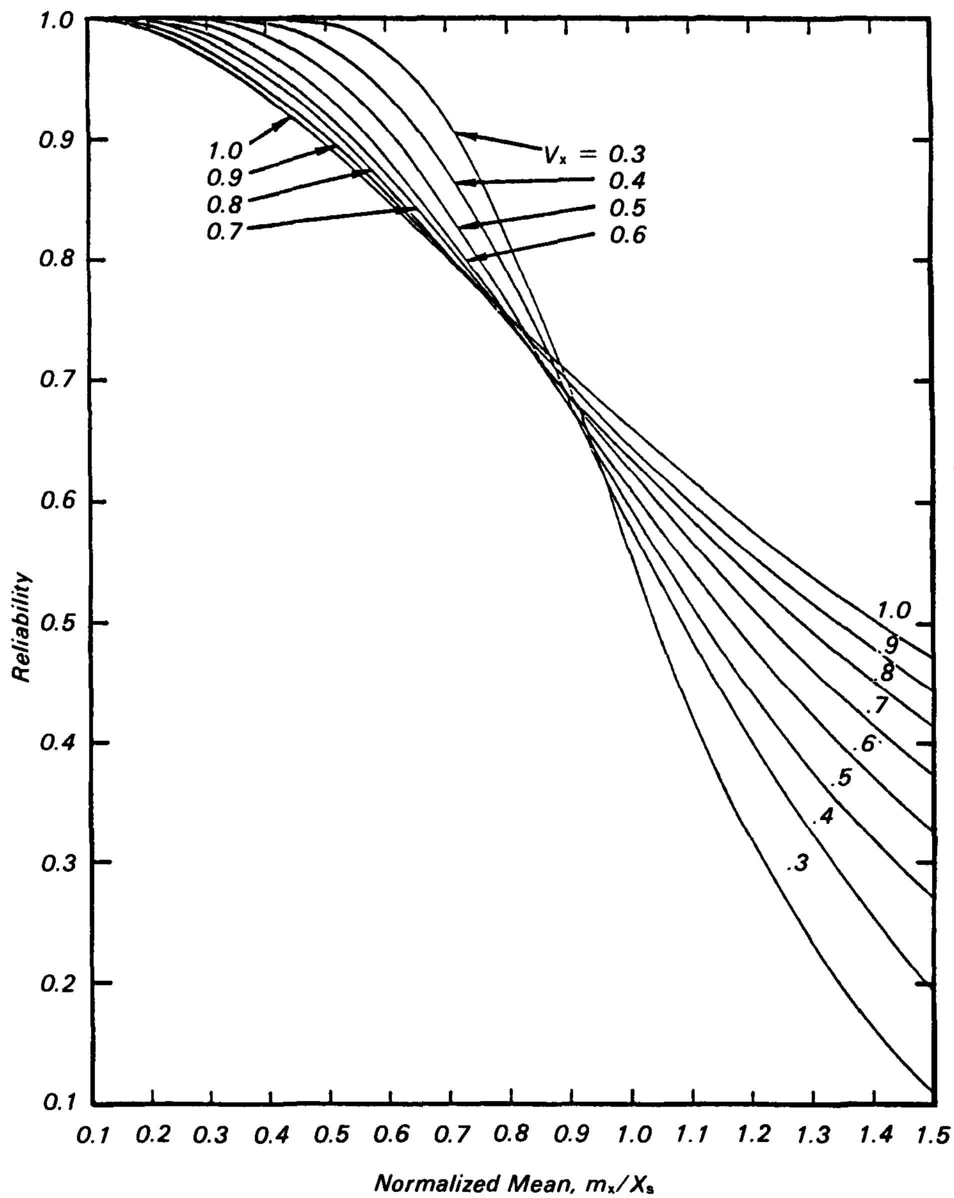

Figure 1. Reliability versus normalized mean for different coefficients of variations.

*Niku, S., E. D. Schroeder, G. Tchobanoglous, and F. J. Samaniego, "Performance of Activated Sludge Plants: Reliability, Stability and Variability," EPA-600/2-81-227, U.S. Environmental Protection Agency, Cincinnati, OH, September 1981.

results of COR based on the log-normal distribution assumption.

Stability of Trickling Filter Plants

Stability is a measure of adherence of the annual mean concentration, and "standard deviation" is the most appropriate measure of stability in wastewater treatment plants.

In Figures 2 and 3, the mean, standard deviation, and range of effluent BOD_5 and SS data for all 11 trickling filter plants are shown. Examination of these descriptive statistics results in the conclusion that a stability cut-off point of 10 g/m^3 can be used. That is, a distinct difference exists between the statistical characteristics of the plants operating below and above the standard deviation of 10 g/m^3. The maximum daily concentrations of effluent BOD_5 and SS in stable plants with a standard deviation of less than or equal to 10 g/m^3 are usually less than 70 g/m^3; whereas in unstable plants, maximum concentrations are usually greater than 90 g/m^3 and 80 g/m^3, respectively.

The full report was submitted in fulfillment of Grant No. R805097-01 by the University of California under sponsorship of the U.S. Environmental Protection Agency.

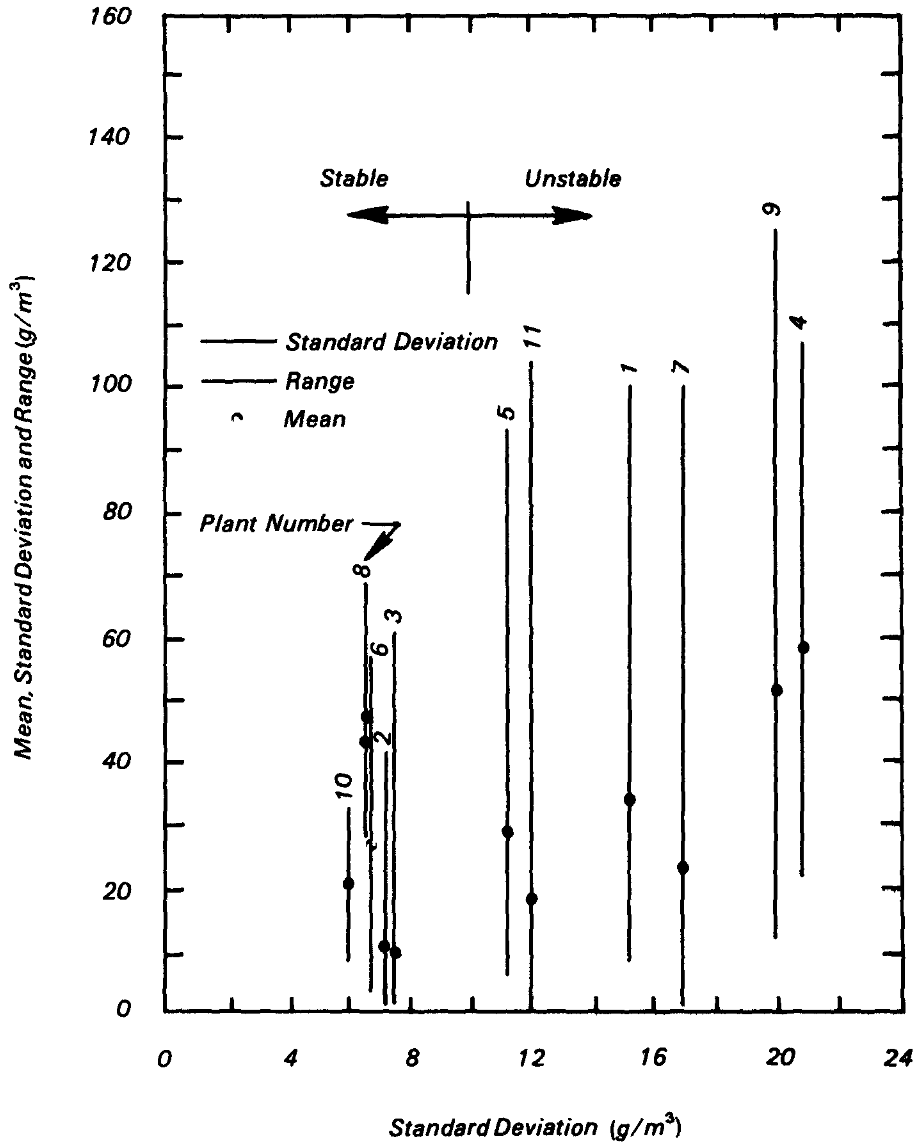

Figure 2. Variability of effluent BOD as a function of standard deviation.

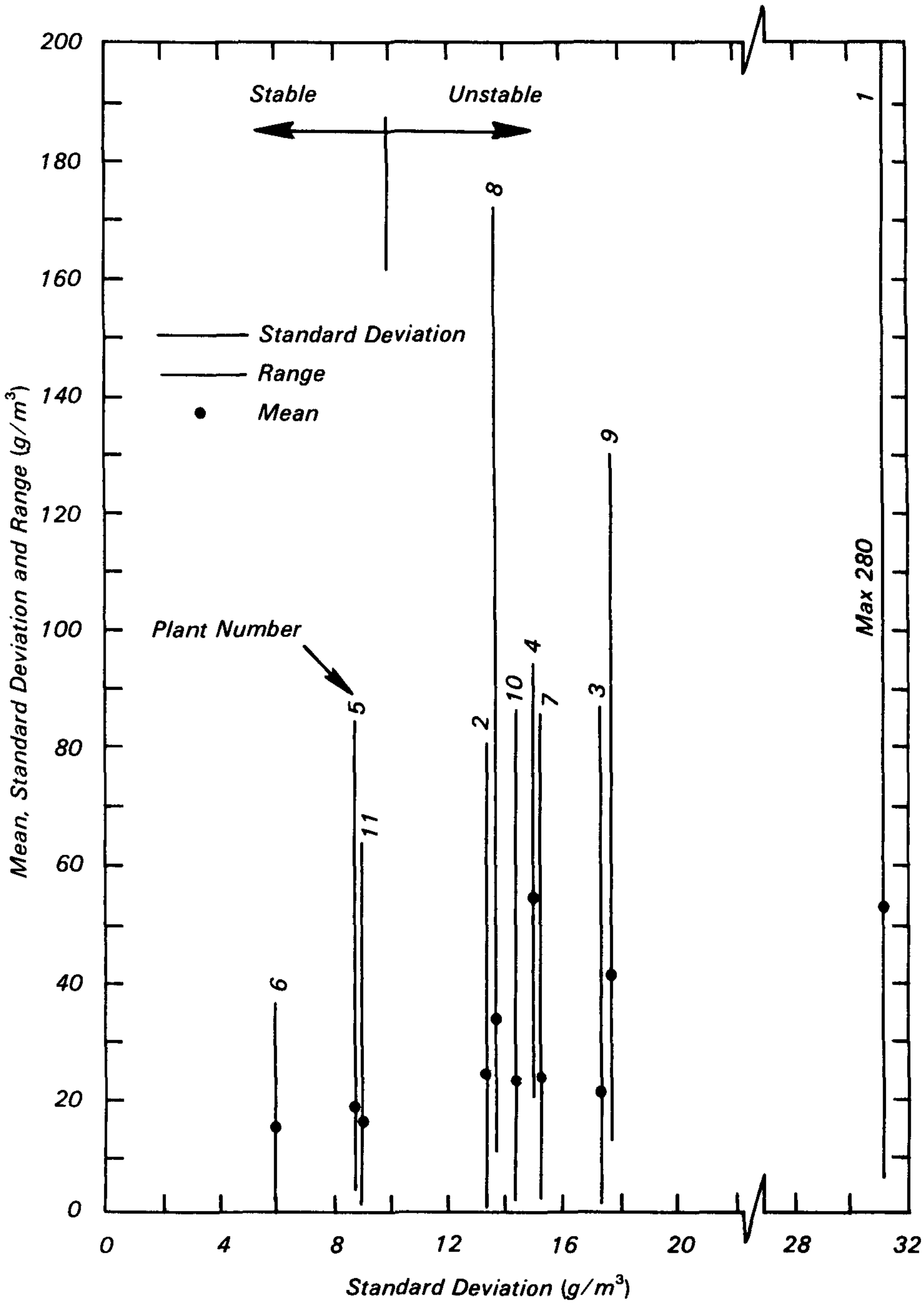

Figure 3. *Variability of effluent suspended solids concentration as a function of standard deviation.*

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The complete report, entitled "Performance of Trickling Filter Plants: Reliability, Stability and Variability," (Order No. PB 82-108 143; Cost: $11.00, subject to change) will be available only from:

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